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RESEARCH MEMORANDUM

(Uncl) IMAGE BRIGHTNESS INTENSIFIERS

Radio Corporation of America
RCA Laboratories Division

RM-1158

10 November 1953

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REPORT

ON

IMAGE BRIGHTNESS INTENSIFIERS

July 23, 1953

Prepared by

G. A. Morton

RADIO CORPORATION OF AMERICA
RCA Laboratories Division
Princeton, N. J.

for

THE RAND CORPORATION

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LEGENDS OF FIGURES

Symbols Frequently Used

Physical

e	charge on electron	1.602×10^{-19} coulombs
h	Planck's constant	6.624×10^{-27} erg sec.
c	velocity of light	2.998×10^{10} cms/sec
λ	wavelength of light	
ν	frequency of light	$(\nu = \lambda/c)$
γ	quantum efficiency	
τ	carrier lifetime	
ρ	conversion factor between light flux and number of photons	
$\mathcal{H}$	certainty coefficient	

Photometric

L	luminoscity	candles
I	illumination	lamberts or candles/cm^2
B	brightness	lumens/ft^2 or foot-candles
$V(\lambda)$	visual response function	
$S(\lambda)$	photoelectric response	(per unit wavelength)
p	photoelectric response	(total)

(subscript i designates image space)
(subscript o designates object space)

The image brightness intensifier, as the [illegible] [illegible], is an instrument for increasing the brightness of the image of a scene beyond the brightness which would be obtained with a passive optical system. Conceptually, such an instrument is very attractive inasmuch as it seems to offer promise of permitting vision under conditions of darkness where the light level is too low for seeing with the unaided eye. Without any analysis, this objective does not seem impossible of attainment inasmuch as it is known that numerous nocturnal animals such as the rhesus monkey, many members of the feline family, owls, etc. can see better at night than can human beings. An owl, for example, can fly at night and seems to be able to see branches and other obstacles with sufficient clarity to be able to avoid them under circumstances where a human being would be nearly blind. These remarks merely serve to point out that a problem does exist. They in no way indicate how or whether it can be solved technically nor do they give any quantitative ideas as to the gain in seeing that might be achieved through an image brightness intensifier.

Before taking up the question of the design of various types of image brightness intensifiers or discussing the experiments which have already been performed along this line, it is necessary to consider in some detail the physical processes underlying vision and image reproduction in order to establish certain theoretical limits. In treating the matter of image reproduction and seeing, the subject will be subdivided as

follows: (A) the physical nature of light and some of the optics involved in imaging; (B) photoactive materials; (C) the statistical nature of image reproduction; (D) the performance of an ideal brightness intensifier.

The discussion of the fundamental limits of image formation and brightness intensification will be followed by a description of various classes of image brightness intensifiers and the problems they present. Next, the experiments which have been tried to date in the image intensifier field will be considered. Finally, an attempt will be made to give a tentative evaluation of the usefulness of this class of device.

PART I

THE FUNDAMENTALS OF IMAGE REPRODUCTION AND BRIGHTNESS INTENSIFICATION

1. Light and Optical Considerations

Light is that portion of the electromagnetic spectrum which lies below ultraviolet radiation and above infrared. The shortest wavelength of radiation which can properly be considered as light would be placed at about 4000 Å, while the maximum wavelength is about 8000 Å. Like other forms of electromagnetic radiation, the total amount emitted by a source may be given in terms of watts. Since the energy of the radiation may vary with wavelength over the visible region, additional characterization is obtained by giving the number of watts per unit wavelength. The radiation intensity, angular distribution, etc. may be similarly characterized.

If the response of the eye were independent of wavelength, it is quite certain that energy units would have been adopted for light. However, this is not the case, and another set of units based upon visual sensation is employed. The primary unit for this system is the candle which is the measure of luminous intensity L for a small source, or power per unit solid angle modified by the visual response curve. The present primary standard "candle" is specified in terms of a carbon fillament lamp operated under defined conditions (originally the Hefner lamp was the primary standard). There are three principal derived units. The lumen, which is the first of these and is sometimes taken as a primary unit, designates the total

light flux F or radiated power modified by the response of the eye. The brightness B of a surface is given in candles per unit area and has the dimension of power again modified by the eye response (lumens) per unit solid angle per unit area of surface. The third derived unit specifies the illumination I of a surface and is expressed in lumens per unit area. Lumens per square foot and the less correct term "foot-candles" are used interchangeably. A secondary derived unit is also convenient. This is the lambert, which specifies the brightness of a perfect diffuse reflecting surface which is illuminated by one lumen per square centimeter.

In order to convert from this special system of units to the more general units of energy or power it is necessary to make use of the visual response curve. Visual response curves have been made for a large number of observers and from these measurements an average visual response curve has been derived. This curve gives the relative sensation of brightness produced by sources of different wavelength radiating the same amount of power in their respective wavelength bands. The form of the visual response curve is given in Fig. 1 while Table I gives the numberical data for this curve. If the spectral output of a given source is $E(\lambda)$ in watts per unit wavelength per unit solid angle, it will have a luminosity given by the following integral:

$$L = \int_0^\infty E(\lambda)\ V(\lambda)\ d\lambda \qquad (1)$$

where V_λ is the visual response function and λ the wavelength of light.

TABLE I

RELATIVE VISIBILITY OF ELECTROMAGNETIC RADIATION

λ	Visibility	λ	Visibility
4000 Å	0.0004	5800 Å	0.870
4100	0.0012	5900	0.757
4200	0.0040	6000	0.631
4300	0.0116	6100	0.503
4400	0.023	6200	0.381
4500	0.038	6300	0.265
4600	0.060	6400	0.175
4700	0.091	6500	0.107
4800	0.139	6600	0.061
4900	0.208	6700	0.032
5000	0.323	6800	0.017
5100	0.503	6900	0.0082
5200	0.710	7000	0.0041
5300	0.862	7100	0.0021
5400	0.954	7200	0.00105
5500	0.995	7300	0.00052
5600	0.995	7400	0.00025
5700	0.952	7500	0.00012

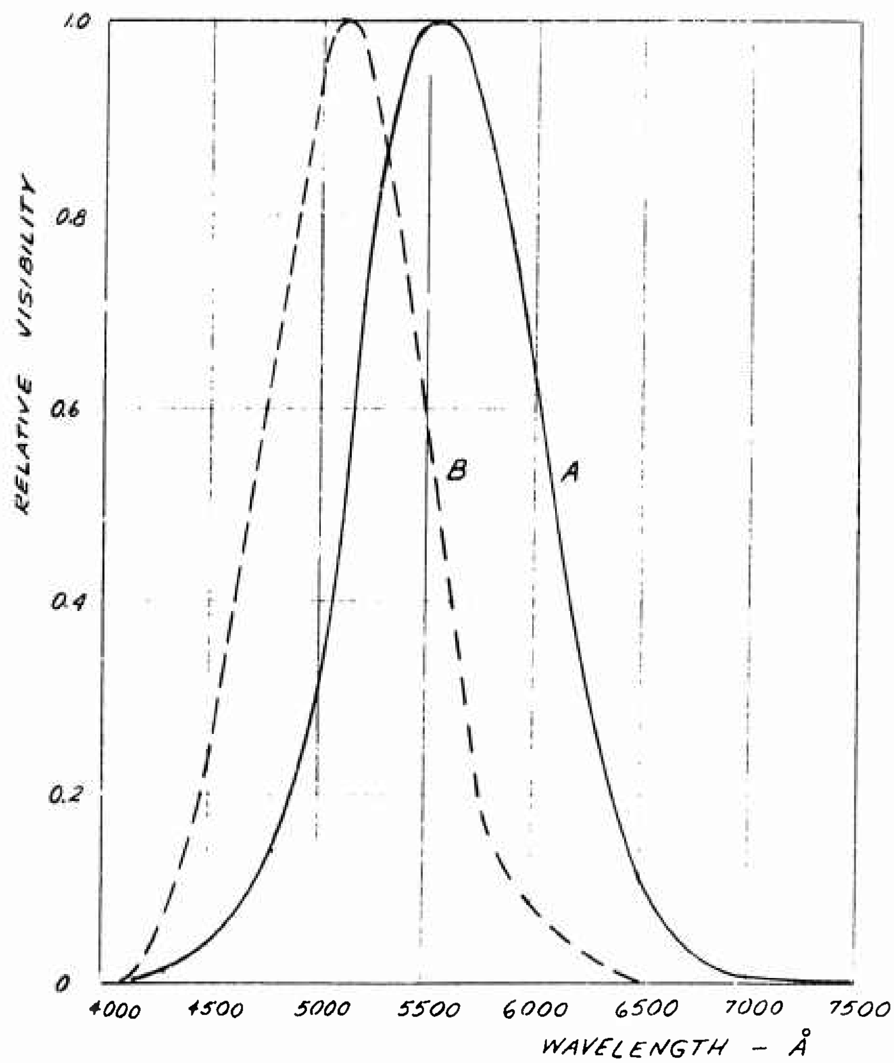

FIG. 1 – VISUAL RESPONSE CURVE

The intensity of radiation as a function of wavelength may vary widely with different sources. Of particular interest here is the distribution of intensity as a function of wavelength for ambient daytime illumination. The distribution for moonlight and moonless nights, while not identical, is similar. Fig. 2 gives the average daytime spectral value for this distribution.

If the radiation from a source having a distribution $J(\lambda)$ (watts per unit wavelength per cm^2) falls on a surface, the reflected light will not necessarily have the same distribution. This is very obvious in the case of surfaces colored by paints or dyes. To determine the amount of radiation reflected under such circumstances, it is necessary to perform the integration indicated in the equation below.

$$H(\theta) = \int J(\lambda)\ R(\lambda\theta)\ d\lambda \qquad \text{watts/unit angle/cm}^2 \qquad (2a)$$

or

$$B(\theta) = A\int J(\lambda)\ V(\lambda)\ R(\lambda\theta)\ d\lambda \qquad \text{lamberts} \qquad (2b)$$

where $R(\lambda\theta)$ is the reflectivity of the surface as a function of angle and wavelength.

A is a constant relating power in watts with lumens at peak of visual response = 621 lumens/watt.

The fraction of incident illumination reflected by surfaces in general may vary widely. A very good white may reflect as much as 99% of the incident energy or even more, whereas an ordinary black surface will reflect only about 1%. It is very difficult to produce whites which are better than 99%. An average

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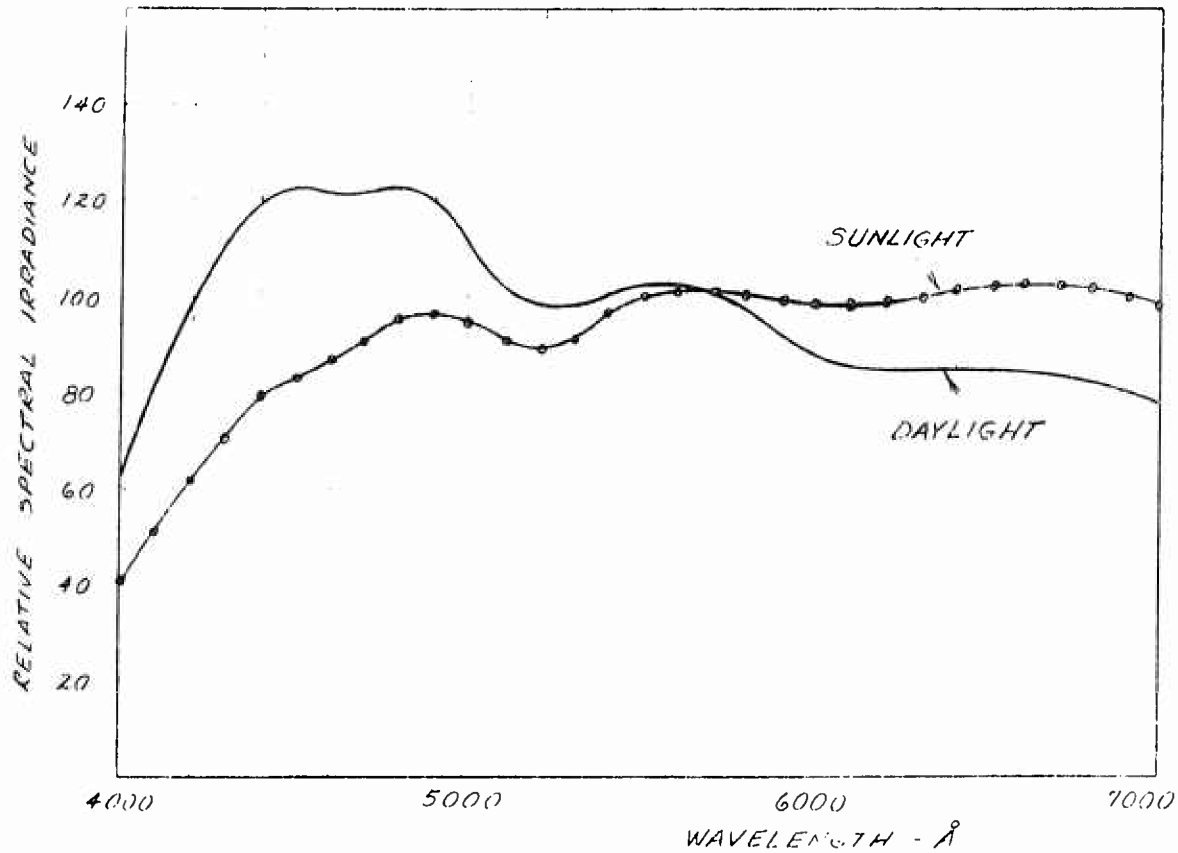

FIG. 2 AVERAGE SPECTRAL DISTRIBUTION OF DAYLIGHT

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outdoor scene reflects between 50 to 70% of the incident light received. If the incident radiation strikes a surface from a particular direction, the angular distribution may vary considerably. The two broad types of reflections are specular reflections and diffuse reflections. A surface which gives specular reflection reemits the incident light in a direction which lies in the plane containing the normal to the surface and the incident radiation and whose angle of emergence is equal in magnitude but opposite in sign to that of the incident radiation. The distribution of light from a diffuse reflector is independent of the direction of the incident light and is distributed symmetrically about the normal to the reflecting surface. The distribution in intensity is given by Lambert's Law, namely:

$$L(\theta) = IR \cos(\theta)\, ds$$

where I is the incident illumination, R the reflectivity and θ the direction of reflection.

One of the properties of this distribution is that a flat surface looks equally bright when viewed from any angle because the foreshortening just compensates for the reduction in amount of radiation from each element of area. While most surfaces encountered in practice combine the two types of reflection (i.e., have a slightly gloss appearance), most of the following discussion will assume diffuse reflectivity. Table II defines some of the common units of illumination and brightness.

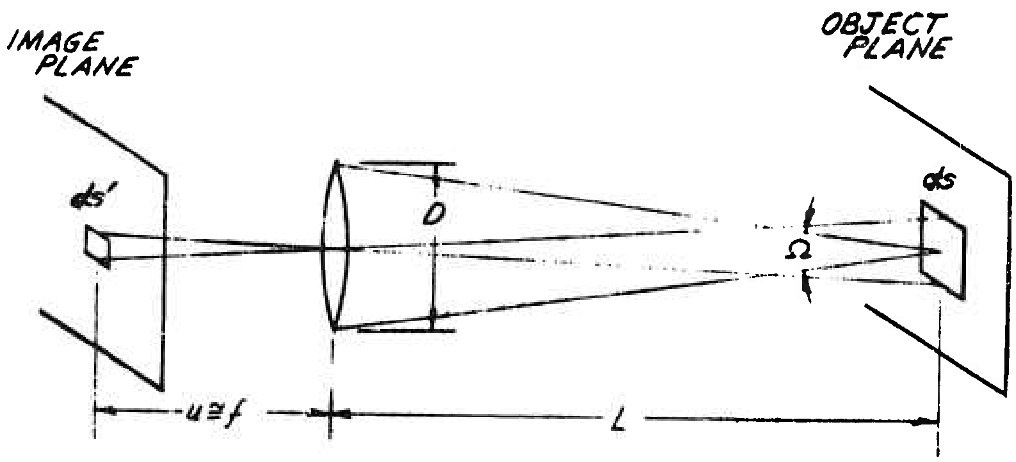
TABLE II

Optical Units

Name	Unit	Dimensions
Luminous Intensity	Candle	Lumen per unit solid angle
Flux	Lumen	Lumen (at max. vis. response) = $\sim$.0015 watts
Brightness	Candles per unit area	Lumens per unit area per unit solid angle
	Lamberts	$1/\pi$ candles per sq. cm.
	Foot Lamberts	.0010764 Lamberts
Illuminations	Lumens per unit area	Lumens per unit area
	Foot Candles	Lumens per square foot
	Lux	10.764 Foot Candles = Lumens per square meter
	Phot	10,000 Lux

Image Formation

The simplest example of image formation is that where an illuminated object is imaged by a simple lens onto a diffusely reflecting surface. This is shown in Fig. 3. It is apparent from the geometrical construction given on the figure that the



$$ds' = \left(\frac{f}{L}\right)^2 ds$$

FRACTIONAL SOLID ANGLE $\Omega = \frac{\pi D^2}{4 \cdot 4 \pi L^2}$

FIG. 3 – SIMPLE IMAGING SYSTEM.

following approximate relationship between the brightness of the object B_o and that of the image B_i is given by:

$$B_i = \frac{I_i}{\pi} = \frac{1}{4} \frac{D^2}{f^2} B_o \qquad (3)$$

where f is the focal length and D the diameter of the lens*. Almost all practical cases of optical imaging can be reduced to this simple form.

In considering the brightness intensifier, it is necessary to introduce one further concept. Heretofore, light has been considered as electromagnetic radiation only. The electromagnetic wave concept of light is entirely adequate for describing the paths that this type of radiation will follow. It will not only account for the light paths of geometric objects but will also give quantitative information about diffraction effects. However, when light interacts with matter to exchange energy, the electromagnetic wave model is no longer completely satisfactory. Instead, it is necessary to assume that light has corpuscular properties. The amount of energy carried by each corpuscle or photon of light radiation is dependent upon the frequency of the light. It is given by the relation:

$$E = h\nu$$

where h is Planck's constant and has a value of 6.624×10^{-34} joule seconds or 4.11×10^{-15} electron volt second and $\nu = C/\lambda$ is the frequency of the radiation.

Another relationship which is very convenient for computing the energy of a photon given the wavelength λ in

*More exactly, the diameter of the entrance pupil.

Angstrom units is:

$$E = \frac{12340}{\lambda} \text{ electron volts.}$$

From the above relationship it will be apparent that radiation at 4000 Å behaves as though it were constituted of photons each with an energy of 3.1 electron volts while radiation at 5550 Å at the peak of visual sensitivity has a photon energy of 2.2 electron volts. At the red end of the visual spectrum, say 7700 Å units, the photon energy is about 1.6 electron volts.

2. Photoactive Materials

In discussing the interaction between light and photoactive materials, it is absolutely essential to employ the corpuscular concept of radiation. This same concept is equally important in the consideration of the generation of light by electron bombardment, chemical processes, or for that matter by any other process, but since the transformation of other forms of energy into light is of only secondary importance here, further discussion will be omitted from the present report.

The most important photoactive processes from the standpoint of the brightness intensifier problem are photoemission, photoconductivity, and the photo-chemistry of the eye.

A. Photoemission

When light falls on certain surfaces, it causes the emission of electrons. All metals are photoemitters, but only a few of them will respond to radiation with wavelengths as long as that which corresponds to visible light. Furthermore, those

which do show photoresponse are very inefficient photoemitters. However, there are a number of complex semiconductor surfaces which are good from the standpoint of visible light photoemission.

The free electrons in a solid are kept from escaping into the surrounding vacuum by a potential barrier. In order for an electron to escape, it must be given sufficient energy so that it can traverse this barrier. Each light photon which enters a surface may interact with an electron giving up its energy. If the amount of energy which the photon contains is greater than that represented by the barrier, the electron may escape. Unless the energy interchange occurs very close to the surface when the material is a metal and unless the kinetic energy given to the electron is directed towards the surface of the metal, the excited electron will simply give up its energy to the metal lattice and return to its normal unexcited level. This is the reason why the quantum efficiency of metallic photoemitters is very low.

Efficient photoemitters are all semiconductors having a filled valence band, a forbidden region, and a conduction band. Furthermore, the potential of outside space is close to the level of the bottom of the condution band or even below it. This is shown schematically in Fig. 4. If a photon has sufficient energy to excite an electron from the valence band into the conduction band, it may remain in the conduction band for an appreciable length of time and during this entire time it has a chance to diffuse out through the surface due to its thermal motion.

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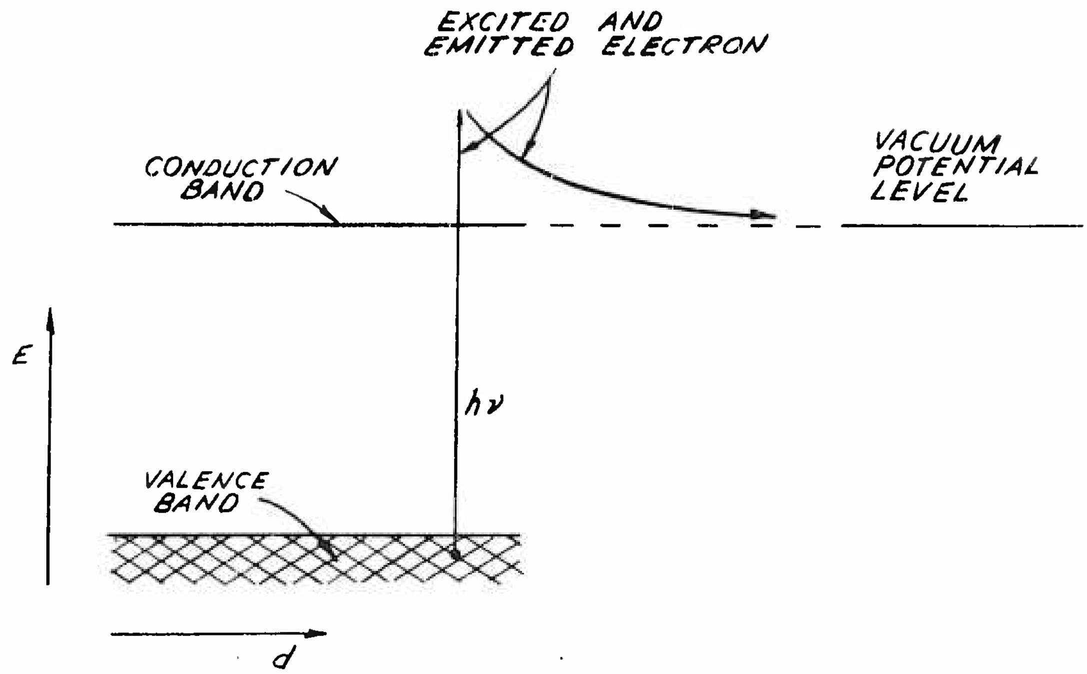

FIG. 4 – ENERGY BAND STRUCTURE OF
SEMICONDUCTOR PHOTOEMITTER.

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Thus, any electrons excited over a considerable volume of the semiconductor may escape as photoelectrons.

Three semiconductor photoemitters are of considerable importance in connection with the brightness intensifier problem. These are Cs_3Sb, Li_3Sb and Cs-CsO-Ag films. The first two mentioned may have quantum efficiencies of 20% or 30% for wavelengths above the minimum required to excite an electron from the filled band to the conduction band. For these two materials, the required photon energy is 2 to 3 electron volts and the response maximum occurs at about 4000 Å. The Cs-CsO-Ag film has much lower quantum efficiency but responds to a much longer wavelength than do the aforementioned two. Photon energies of between 1 and 1.5 electron volts are needed to excite photoemission from such surfaces. The peak of photosensitivity for silver cesium surfaces is at a wavelength of about 8000 Å and some response is obtained beyond 12,000 Å.

B. Photoconductivity

The second type of photoelectric phenomena which is important to the present problem is photoconductivity. A photoconductor is a semiconductor in which current carriers, either holes or electrons, can be excited by the action of light. Intrinsic photoconductivity is where an electron is excited from the valence band into the conduction band leaving a mobile hole in the filled band. Impurity photoconductivity occurs when there is an impurity state in the forbidden gap. This may be a donor state and the excitation raises its electron into the conduction band or it may be an acceptor level in which case

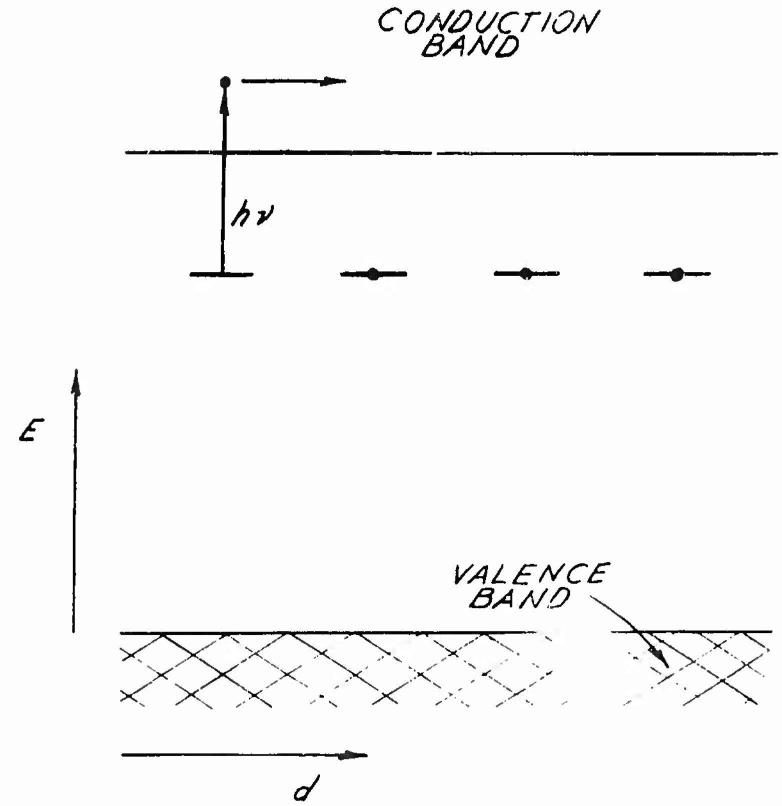

FIG. 5 – ENERGY BAND STRUCTURE OF IMPURITY (n-TYPE) PHOTOCONDUCTOR.

the radiation causes an electron from the filled band to be excited into the acceptor level.

The primary quantum efficiency of a photoconductor is the ratio of number of excitations to number of incident photons. After an excitation has taken place, a current will continue to flow until the current carrier is captured and recombines. For example, a donor impurity may be excited and the electron move in the conduction band to the positive junction of the photoconductor. As the electron moves out of the photoconductor a new electron enters through the negative junction because of the positive charge on the ionized donor center. This will continue until the ionized donor center captures an electron. Thus, in many photoconductors hundreds, and even thousands, of electrons may traverse the photoconductor from the negative junction to the positive junction as the result of a single excitation. Therefore, the secondary quantum of efficiency which is the number of electrons coming from the photoconductor per photon absorbed, may be much larger than unity, although the primary quantum efficiency cannot under any circumstances exceed one.

The current from a photoconductor will be given by the following relation:

$$i = e\frac{\tau\mu V}{\ell^2}\gamma I \quad , \qquad (4)$$

Here γ is the primary quantum efficiency, μ the mobility, ℓ the length of the crystal, τ the lifetime of the excited carrier, V the potential difference between the two junctions and I the illumination per unit length.

The spectral response of a photoconductor is determined by the energy gap through which a carrier must be excited. In general, there is a long wavelength limit where the photon energy just equals the gap. Radiation with wavelengths shorter than this has a high quantum efficiency, while below this wavelength value the response drops rapidly to zero. In discussing various modifications of the brightness intensifier involving either photoemission or photoconductivity, an average quantum efficiency will be required. The average quantum efficiency $\overline{\gamma}$ can be determined by performing the indicated integrations in the following expression:

$$\overline{\gamma} = \frac{1/e \int P(\lambda)\ S(\lambda)\ d\lambda}{1/hc \int P(\lambda)\ \lambda} = \frac{hc}{e} \frac{\int P(\lambda)\ S(\lambda)\ d\lambda}{\int P(\lambda)\ \lambda d\ \lambda} \qquad (5)$$

where the symbols have the following significance:

$S(\lambda)$ response of photoconductor (amperes/watt/unit wavelength)

$P(\lambda)$ power of radiation (watts/unit wavelength)

h, c, e Planck's constant, velocity of light and electronic charge (coulombs).

As will be discussed in further detail later, the sensitive elements in the retina of the eye can be assigned a quantum efficiency in much the same way as has been done for photoconductors and photoemitters.

3. Image Recognition

Let us consider what is implied in the recognition of the context of an image. Fig. 6 is a diagram of the formation of an image of an object consisting of two illuminated squares which reduces the problem to its essential elements. This very simple, basic concept is sufficient to establish limits of what may be done with a brightness intensifier. The two areas being imaged have slightly different brightnesses. Consequently, their images also receive different illumination. The problem is to determine under what circumstances this difference in illumination can be detected and, furthermore, as to whether there are fundamental limits beyond which detection becomes impossible.

If n_a is the number of photons reaching image A, and n_b that at image B per second per unit of time, there will be $n_a \gamma t$ detectable event in image area A and similarly in B there will be $n_b \gamma t$ countable steps. Except for the statement of primary quantum efficiency γ the means of detection need not be specified.

Our ability to distinguish between A and B rests upon being able to note a significant difference in the count for the two image areas. To determine whether a difference in count is significant, it is necessary to resort to the fundamental statistics of the situation. The emission or arrival of photons is a purely random phenomenon. Each photon has a certain probability of arrival and this probability is independent of the arrival of other photons. Thus, when we say that n_a photons

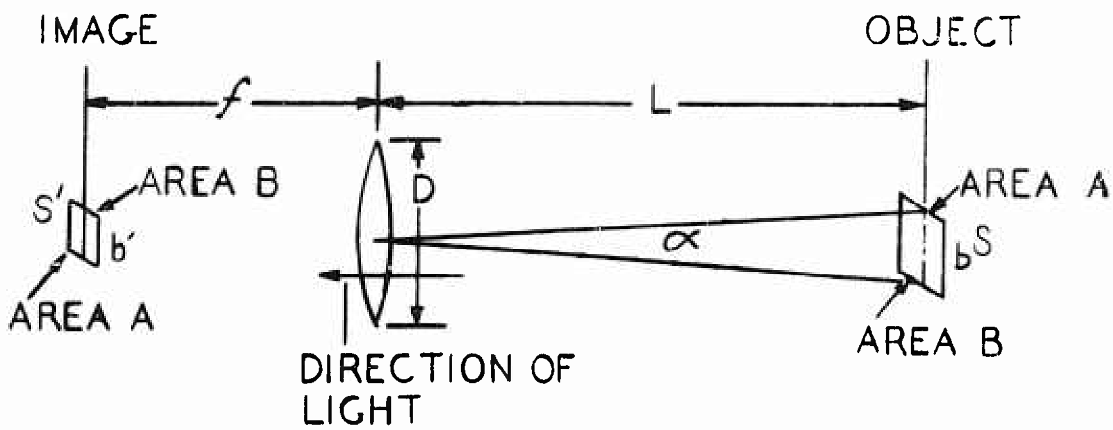

FIG.6 – LENS SYSTEM FOR DETERMINATION OF STATISTICAL LIMITATION OF VISION.

arrive per second on area A, what is actually meant is that the expected number is n_a. If the number is counted second by second, the number would be found to be different. There would be a root-mean-square deviation in n_a proportional to the square root of n_a, the mean value. In comparing the two areas, A and B, the difference in the number of countable events during a fixed predetermined integration time will be a measure of our ability to distinguish between them. The integration time t may simply be the storage time of a viewing device; the persistence of vision of the human eye; or the response time of an amplifier as determined by its frequency bandwidth. If the difference between the number of events in the two areas is small compared to the root-mean-square deviation in number of the events in either area, it will be impossible to say whether the difference is simply due to statistical fluctuations or whether it is a real difference at the object.

The factor $\mathcal{K}$ by which the difference exceeds the root-mean-square deviation is a measure of the certainty that the difference observed is a true difference. If $\mathcal{K}$ has a value of 5, the probability that the difference is real exceeds 95%. For practical purposes, we shall say that if the difference equals 5 times the root-mean-square deviation, that is, 5 times the square root of the number of events, the two surfaces can be distinguished.

The next step is to put this concept of the statistical requirement for image or contrast recognition into more rigorous optical terms. This can be done as follows:

Contrast is defined as the difference in brightness between two areas divided by the brightness itself. Thus, if an area has a brightness B and an adjoining area of brightness B_1 the contrast C between the two is:

$$C = \frac{B - B_1}{B} = \frac{\Delta B}{B} .$$

Let us examine the optical system shown in Fig. 6 to determine the minimum contrast that can be detected on the basis of the foregoing, as a function of brightness, quantum efficiency, lens aperture, etc. The small object S will be the area imaged. For simplicity, instead of comparing the brightness of two adjoining areas, we will determine the smallest brightness change ΔB that can be determined when the brightness level is B. An image S' is formed of S on the detector surface. This detector surface may be the retina of the eye, the cathode of a converter tube, the target of a pickup tube, etc.

Referring to Fig. 6, D is the diameter of the lens whose focal length is f. The object distance L is large compared with the focal length of the lens so that the image position is essentially at the focal point of the lens. The object is assumed to be a square whose sides have a length b and which subtends an angle α at the lens.

If B is the brightness in lamberts, the number of lumens leaving the object area per unit solid angle (normal

to its surface) is Bh^2/π. If now ρ is the conversion factor between lumens and effective number of photons, the number of photons per second n_s passing through the lens will be:

$$n_{s'} = \frac{\rho}{\pi} \frac{\pi D^2}{4\pi L^2} Bb^2 \quad .$$

All of these photons fall on the image area S'.

Any detecting device will have an integration time t. In the case of the eye it is the time of the persistence of vision. Therefore, the number of photons reaching S' in the integration is:

$$N_{os'} = \frac{\rho t}{4\pi} \frac{b^2}{L^2} D^2 B = \frac{\rho}{4\pi} t\alpha^2 D^2 B \tag{6}$$

where the angle subtended at the lens by the object is $\alpha = \frac{b}{L}$ assuming α to be small.

As has been pointed out in earlier sections, not every photon necessarily produces a detectable event. Therefore, a quantum efficiency γ must be assigned which gives the fraction of photons producing a countable effect. The number of countable events at s' for a brightness B is therefore:

$$N_s = \frac{\gamma\rho}{4\pi} t\alpha^2 D^2 B \quad .$$

The statistical argument given above concluded that the smallest change ΔN_s in the number, which could be detected with reasonable certaintity, is:

$$\Delta N_s = \mathcal{K}\sqrt{N_s}$$

where $\mathcal{K} \sim 5$ is the certainty coefficient.

We are now in a position to express the minimum contrast which can be detected in terms of the various optical parameters.

$$C = \frac{\Delta B}{B} = \frac{\Delta N_s}{N_s} = \mathcal{K}/\sqrt{N_s}$$

$$= \mathcal{K}/\sqrt{\frac{\rho\gamma}{4\pi} t\alpha^2 D^2 B} \qquad (7)$$

or in other words

$$BC^2D^2\alpha^2 t\gamma = \frac{4\pi\mathcal{K}^2}{\rho} = \text{const.} \qquad (8)$$

It is interesting to put numbers into the above relationship to see how it compares with the measured performance of the eye. Two cases will be considered, the first where the light level is very low, so that visual acuity is only about 1°, the other under conditions of normally good seeing.

The following values can be assigned to the various constants Eq. 8.

Quantum efficiency of the eye	$\gamma = 0.1$
Photon conversion factor	$\rho = 1.3\times10^{16}$
Certainty coefficient	$\mathcal{K} = 5$
Persistence of vision	$t = 0.1$

For case I, the conditions which are assumed are:

minimum contrast $C = \sim 1$

$D = 0.6$ cms

$\alpha = 1^\circ = .018$

The problem here is to determine the brightness which satisfies the above conditions. This brightness should be very close to visual threshold.

$$B = \frac{4\pi\mathcal{K}^2}{\rho C^2 D^2 \alpha^2 t} = \frac{12.6\times25}{1.3\times10^{16}\times.36\times3.1\times10^{-3}\times10^{-1}\times10^{-1}} = 2.2\times10^{-9} \text{ lamberts.}$$

This corresponds to the illumination of a white surface with 2.5×10^{-6} lumens per square foot. This figure is within an order of magnitude of the visual threshold (frequently assumed to correspond to an illumination of 10^{-5} lumens/ft^2).

For case II, the conditions assumed are as follows:

$B = 10$ ft. lamberts $= 10^{-2}$ lamberts

$D = 0.1$ cm

$\alpha = 1' = 3 \times 10^{-4}$

from which it is possible to compute the minimum perceptible contrast.

$$C = \sqrt{\frac{4\pi\, \delta^2}{\rho \gamma t}} \times \frac{1}{\alpha D\sqrt{B}} = 1.6 \times 10^{-7} \times \frac{1}{3 \times 10^{-4} \cdot 10^{-1} \cdot 10^{-1}}$$

$$C = 0.5 \times 10^{-2}$$

This is probably very close to the actual limit of contrast perception, although again there may be a small error on the side of too great contrast perception.

Where the detection limit is being computed for a photoemissive device such as an image converter intensifier, the result can be obtained by determining the number of photons and employing the quantum efficiency of the photosurface. It is, however, frequently simpler to make use of the measured photosensitivity (in amperes per lumen) and directly compute the number of electrons involved. These electrons are, of course, the "countable event" which determines the threshold for this class of device.

For brightness intensification which is based upon a photoconductor the situation is in practice somewhat more complicated. The fundamental limit is, of course, the primary quantum efficiency of the photoconductor. However, most photoconductors have noise in excess of that indicated by primary quantum efficiency. Hence, in computing the limit of contrast detection, the calculation must be based upon the measured noise and measured response. As the study of photoconductors progresses the noise output will inevitably approach that set by primary quantum efficiency. Indeed, in some especially prepared laboratory samples, statistical fluctuations with an rms value of not more than two or three times fundamental noise have been observed.

Examining the available data, one finds that over the brightness range extending from about 10 ft. lamberts to the threshold of seeing, the eye performs as though it were a device having a quantum efficiency of 10% and limited in its perception only by the statistical nature of photoactivity both for its acuity and contrast perception. The eye, therefore, is a very wonderfully engineered image sensing device. It operates at the noise limit of performance over a least six orders of magnitude range in brightness. In spite of its response approaching so close to fundamental noise, a viewer is rarely aware of noise in the scene before him. There appears to be some form of gain control between the sensing element and the perception region of the brain which very accurately keeps noise just below perception level over this enormous range of

input signal. Furthermore, there is an area integration mechanism which comes into operation in the eye under conditions of low light so that as the illumination decreases, larger and larger areas on the retina cooperate to give noise-free information from the relatively small number of photons entering the eye.

The conclusions noted in the preceding paragraphs are of fundamental importance in considering what can be accomplished with a brightness intensifier. If one postulates an ideal brightness intensifier consisting of a sensitive surface having a quantum efficiency γ means for increasing the brightness of each picture element without adding any further noise or fluctuations to the resulting picture and an ocular for viewing the intensified image, its performance can be directly compared with that of the unaided eye and its realm of usefulness can be rather clearly delineated.

If the absolute aperture of the lens used to form the image on the sensitive surface of the intensifier is the same as that for the eye and if the quantum efficiency is 10%, it is quite evident that irrespective of the intensification occuring between the sensitive screen and the viewing area, the device will not make it possible to see objects at lower light levels than can be seen with the unaided eye. At low light levels both devices will be limited by the statistical nature of the photo effects. Actually, under these conditions, the intensifier would probably do harm rather than good since it would raise the brightness of the viewed image with a consequent decrease in the area integration properties of the retina of the eye.

The maximum aperture of the pupil of the eye is limited by the construction of the eye itself. No purely optical device can increase the effective numerical aperture of the eye. On the other hand, very large lenses with increased light-gathering power may be used with the brightness intensifier. By this means increased sensitivity can be obtained but only at the expense of depth of focus.

It is clear from the derivation above that the total number of photons received from an object of given area at the image area of this object depends only upon the absolute diameter of the lens. Consequently, the system may be made very sensitive by using a large, long focal length lens and a considerable reduction in the size of the viewing screen over that of the sensitive area so that the net magnification of the instrument is unity. Very great increases in sensitivity may be thus gained. The ratio of sensitivity of this type of telescope intensifier to the sensitivity of the unaided eye is given by the following expression:

$$R = \frac{B_{int}}{B_{eye}} = \frac{D^2_{eye}\,\gamma_{eye}}{D^2_{int}\,\gamma_{int}} = .04/D^2_{int}\,\gamma_{int} \tag{10}$$

where D_{int} is the diameter of the intensifier objective and γ_{int} its quantum efficiency. This assumes a given angular resolution and contrast.

By the increase in flexibility of permitted optics, therefore, the intensifier can increase visual sensitivity. Increased sensitivity may also be obtained from the fact that

some of the photoelectric phenomenon which might be used can have higher quantum efficiencies than does the eye.

So far the discussion of the value of a brightness intensifier has centered around a consideration of the limiting sensitivity. Under some circumstances, there may be a convenience value of an instrument of this type. If the intensification is considerably above that required to present all of the information available from the scene, this added brightness, while giving no further basic information, may make it possible for an observer who is not dark-adapted to see under conditions of illumination which would normally require a maximum of dark-adaptation. In fact, the observer may even be working in a well-lighted room while observing a scene at very low light levels picked up by a remote telescope. Thus, one may distinguish between useful brightness intensification and convenience brightness intensification.

Finally, if the intensification is carried too far, the statistical fluctuations in the reproduced image may become so large that they confuse the observer. This might be termed "destructive intensification".

PART II

BRIGHTNESS INTENSIFIERS

The three elements which are essential to any form of an electronic brightness intensifier are a light sensitive screen, a gain or amplifier element, and a means for presenting the information. The most critical element is the light sensitive screen. It is essential that it have a high quantum efficiency and that its spectral response be suitable for the ambient condition under which the instrument must operate. The response time of the photoelectric element is not critical except that it must not exceed the response time demanded of the overall instrument. While there are many photoelectric effects, only two of them have been sufficiently developed to warrant any consideration as the sensitive elements of an intensifier. These are photoemission and photoconductivity. A number of different intensifiers based on each of these effects will be considered.

The gain or amplifier element may take any one of a number of different forms and a single intensifier may employ several different types of gain mechanisms in its operation. One property which must be common to all of them is that of not introducing additional noise. Furthermore, the gain element must satisfy such obvious requirements as speed, range, linearity, etc.

The presentation means of a brightness intensifier may also take any one of several forms depending upon the problem which is to be met by the instrument. The two forms which will

be considered in greatest detail here are a direct image seen through an ocular and a video signal output which can be reconstructed into an image by conventional television techniques. It is obvious that the direct view system can be readily modified for photographic or zerographic recording and that the output of an instrument which produces a video signal can be used for control purposes or can be recorded by facsimile or ultrafax techniques.

1. Photoemissive Image Intensifiers

Having established certain principles relating to image intensifiers, let us next examine the various types of instruments which may be used to increase the brightness of a reproduced image. The first broad class of these devices depends for its primary conversion of light into an electrical effect upon photoelectric emission. There are a number of intensifiers which fall within this classification and some have been examined in considerable detail both experimentally and theoretically.

A. Image Converter Tube

The simplest photoemissive intensifier is an image converter tube. It consists essentially of a photocathode, an electron optical system and a phosphor screen. When an optical image is formed on the photocathode, electrons are emitted with a density distribution which reproduces the distribution of illumination in the image. These electrons are accelerated to a high velocity by the electron lens system and focused onto the fluorescent screen. Since the brightness of the fluorescence

of the phosphor screen is proportional to the electron density, a reproduction of the original image is formed as a luminous image on the phosphor screen.

The brightness intensification here is obtained because of the energy which is added to the electrons when they are accelerated by the lens system. A converter tube operating at 20 kilovolts and employing a Cs-CsO-Ag cathode will generate 8 to 10 lumens at the fluorescent screen for each lumen which falls on the photocathode. With a high efficiency cesium-antimony photocathode and with illumination having the spectral distribution of ordinary daylight, the lumen conversion factor of an image tube may be 20 to 40. If a simple image tube with unity magnification is used in a telescope having an objective with an F-number or numerical aperture F, the relationship between the brightness of the scene B_o and the brightness of the reproduced image B_i will be given by the following relation:

$$B_i = \frac{G}{4F^2} B_o \tag{11}$$

where G is the lumen gain of the image tube.

The lumen gain G is related to the photosensitivity p of the photocathode for the radiation illuminating the scene, the voltage of the tube V and the efficiency Q of the phosphor screen as follows:

$$L_i = pQVL_o = GL_o$$

There are many types of image converter tubes which might be used in this way. Fig. 7 illustrates three general

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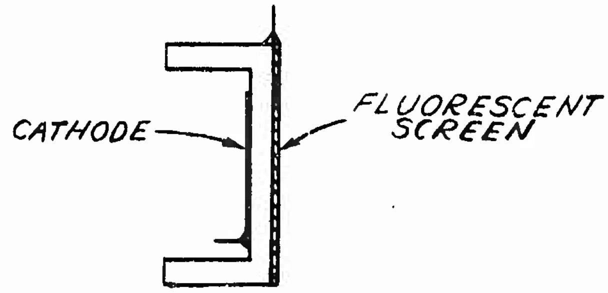
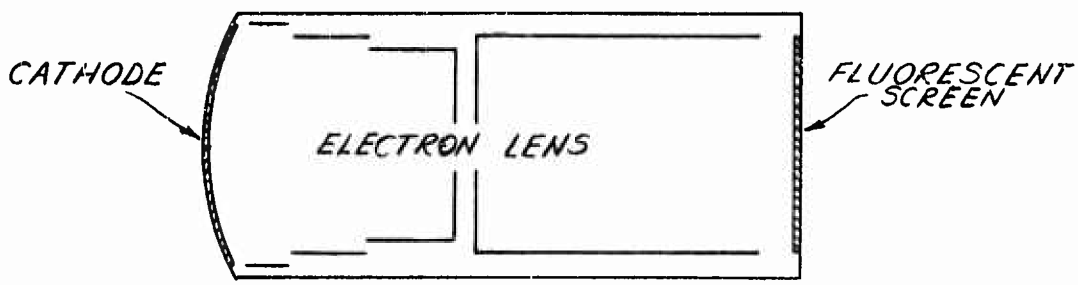
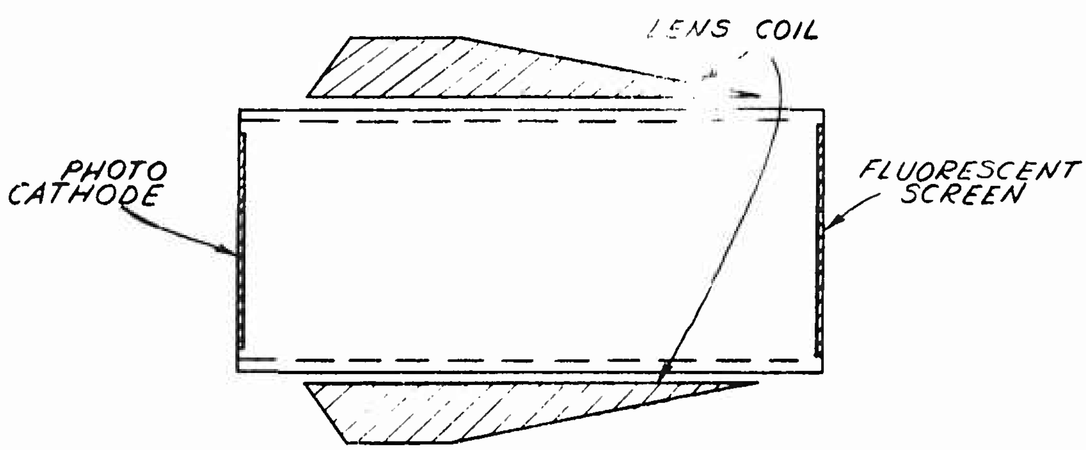


SIMPLE UNIFORM FIELD



ELECTROSTATIC LENS



MAGNETIC LENS

FIG. 7 — IMAGE CONVERTER TUBES

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classes. (A) is the simplest. This tube depends for its image formation simply upon the acceleration of electrons from the cathode to the fluorescent screen by a plane parallel electrostatic field. The type (B), employing electrostatic electron optics, is the most widely used. The electron lens employed here behaves exactly analagously to an ordinary light lens. An inverted electron image of the light distribution of the photocathode is produced at the fluorescent screen. This, of course, is useful when the tube is employed in a telescope since the objective which images the scene before the telescope upon the photocathode also inverts the image. The double inversion leads to an erect image on the phosphor viewing screen. Type (C) is a magnetically focused image tube. While the magnetic tube produces a sharp, undistorted image, this class of focusing means has not been widely used in image tubes for two reasons. First, its weight is considerably greater than that of the electrostatic electron optics and second, it is usually difficult to obtain an image which is either erect or inverted with respect to the distribution on the photocathode. In general, the image will be rotated through an arbitrary angle θ which depends upon the extent to which the lens is either a long or short magnetic lens.

Both the electrostatic and magnetic electron optic are capable of giving images with resolutions of 2000 lines (television standards) or more. This resolution is ample for most practical purposes. These tubes have been used extensively in telescopes designed to reproduce scenes illuminated by near infrared radiation in visible images. They have not been used

as brightness intensifiers because the overall brightness gain in practical telescope systems is not sufficient to warrant this application.

B. Low Magnification Brightness Intensifiers

This class of image tubes resembles those discussed in the preceding paragraph except that the magnification of the electron optical system is made to be fractional. All of the electrons from a large area photocathode are focused by the electron lens into a small area on the viewing screen. This results in a higher current density at the fluorescent screen than would be the case if the magnification of the tube was near unity. The brightness of the reproduced image under these circumstances is greater than for a unity magnification tube by the reciprocal of the square of the magnification. The small image on the fluorescent screen is viewed through an ocular which magnifies it up to a large size without any decrease in brightness as long as the exit pupil of the ocular is equal to or greater than the opening in the iris of the eye.

At first sight it might seem that the increased brightness achieved by the fractional magnification in this type of image tube violates the well known law of optics that an image cannot be brighter than the object. However, when it is recalled that the photoelectrons leave the photocathode with very low energy and thus behave as light rays in a medium of low index of refraction, while they arrive at the phosphor screen with high energy corresponding to light rays in a region of high index, it will be seen that this is not a violation of this

optical principle. The relationship between the brightness of the scene viewed and the brightness of the image seen through the ocular is given by the following relation:

$$B_1 = \frac{G}{4F^2M^2} B_0 \quad . \tag{12}$$

It is identical with that for the simple image tube except for a factor which is the square of the reciprocal magnification (M).

This type of intensifier was explored during World War II and was found to be not altogether satisfactory. The required brightness gain could easily be achieved. However, the increased angular aperture of the electron rays through the lens made it difficult to reduce spherical abberation to a point where the definition of the image was adequate. Close to the threshold of vision, it was found that there was very little difference in the ability to see using this type of telescope as compared with direct vision with the unaided eye. Since the war, some experiments have been continued by Westinghouse and by Philips on this form of intensifier for application to the problem of x-ray image intensification.

C. Cascaded Image Intensifier

The cascased image intensifier is probably the one which has received the greatest amount of study. It consists in principle of a series of image tubes similar to those described under (A) arranged so that the first cathode sees the scene under observation while the cathode of the second is optically coupled to the phosphor screen of the first image tube, the cathode of the third to the phosphor screen of the

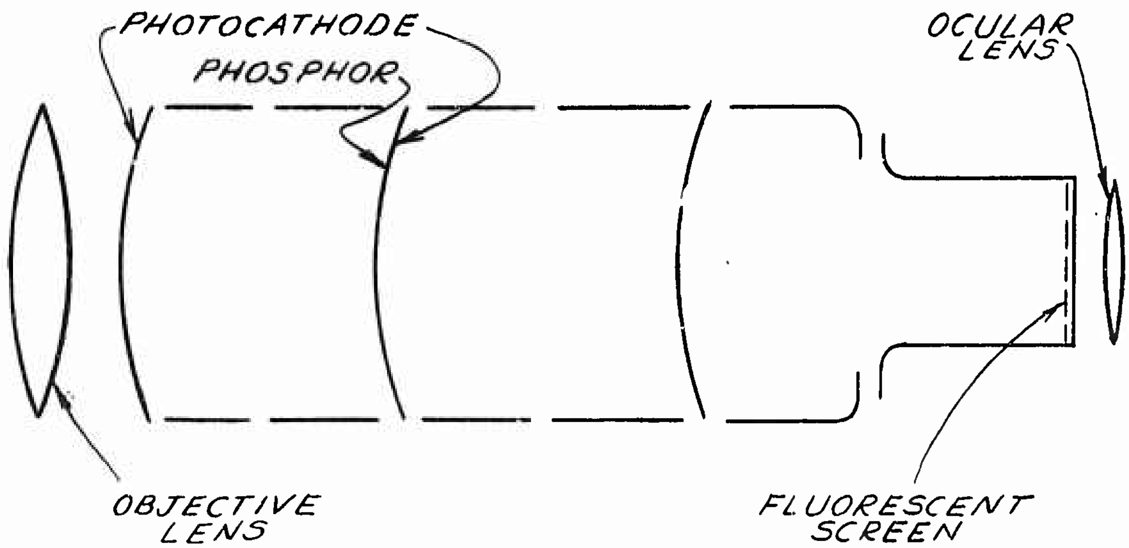

FIG. 8 — CASCADE INTENSIFIER.

second, and so on. The arrangement is shown schematically in Fig. 8. In order to obtain good optical coupling between the screen of one image section and the photocathode of the next, the phosphor screens and cathodes are formed as a combined unit in the following way.

A very thin transparent sheet, either of glass or mica, forms the supporting layer of the structure. The photocathode is deposited on one side, usually in the form of a cesium-antimonide film. An efficient blue phosphor matching the spectral response of the photocathode is formed as a layer on the opposite side of the film. Finally, a thin layer of a light metal which prevents the contamination of the screen during tube processing, stops optical feedback, and increases the efficiency of the fluorescent screen is placed over the phosphor. The general arrangement of this composite, phosphor-photocathode screen is shown in Fig. 9. The transparent supporting membrane must be thin enough (comparable in thickness to the thickness of the phosphor screen) so that there is little degradation in image resolution. The optical efficiency of this arrangement is very high since almost all the light from the phosphor screen goes through the cathode. By using a high efficiency blue phosphor (zinc-sulphide, silver-activated) and a cesium-antimony photocathode (30 microamps. per lumen) a current gain of 10 or more can be obtained at each screen with bombarding electrons of 10 kilovolts. A tube of this type employing two double-layer screens and an overall magnification of 1/10 will have a total brightness gain of 10,000.

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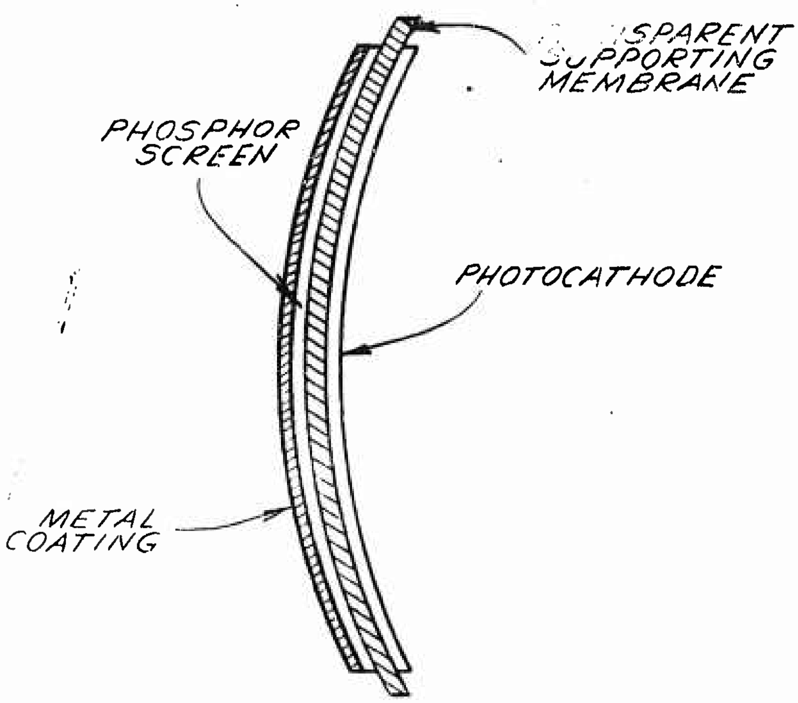

FIG. 9 – CASCADE INTENSIFIER SCREEN.

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Experimental telescopes using Schmidt type reflective optics and cascaded intensifier tubes have shown that it is possible to exceed the performance of the eye by quite a large factor. A detailed description of this type of telescope and tube together with a discussion of the tests that have been made with them will be presented in a later section.

D. Secondary Emission Image Intensifiers

The phenomenon of secondary emission offers another possibility of amplifying the current of an electron image. One form of secondary emission image intensifier is shown in Fig. 10. It consists of an image section with a photocathode and lens system very similar to that of an ordinary image tube. The electron image is formed on a secondary emitting target instead of a fluorescent screen. The secondary electrons are focused by another electron lens system onto a fluorescent screen. A current gain of 5 to 10 times may be obtained from a secondary emission target and the brightness of the image is intensified accordingly. The principal difficulty that has been found in this type of intensifier is that the initial velocity of the secondary electrons is so high that the chromatic abberation in the final image reduces the resolution to a low value. An experimental tube based on this principle employing electrostatic lenses both for the primary and secondary image gave a final image whose resolution corresponded to only about a 100-line television picture. The quality of the image was too low to make the tube practical.

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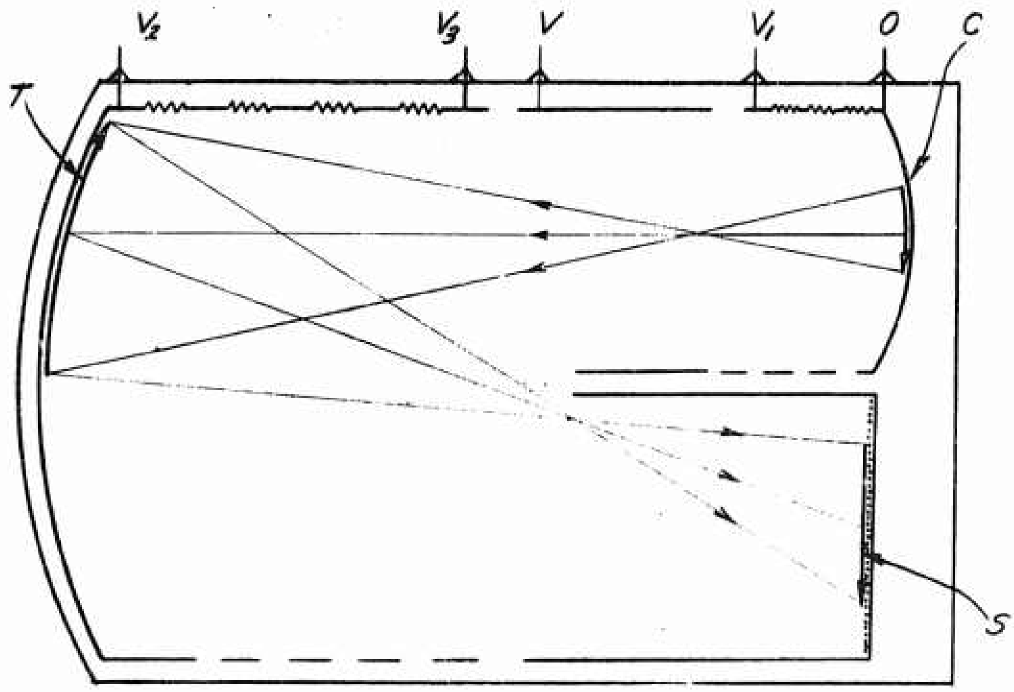

FIG. 10 – SECONDARY EMISSION IMAGE INTENSIFIER.

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Other types of secondary emission intensifiers have been investigated. Fig. 11 shows one based on screens which have been treated to have high secondary emission ratio. Here the focus is magnetic. However, it has been found that under conditions where reasonable definition can be expected in the final image the efficiency of the secondary emitting screen is very low. The results with this type of intensifier have not been at all promising. Conceptually, with present techniques for making fine mesh screens with complicated cross-sectional shapes, an intensifier might be possible where every picture element was a tiny secondary emission multiplier. No experimental work has been done along this line.

E. The Image Amplifier

In all of the intensifiers discussed above, the primary current which, after amplification, was used to form the final image came from a photocathode upon which the scene under observation was imaged. The image amplifier involves a somewhat different principle. Here, the initial photocurrent is used simply to establish the potential of a two-dimensional control grid. The electrons which form the final image come from a separate cathode, are spacially modulated in passing through the two-dimensional control grid and then are directed onto the final viewing screen.

In principle, this arrangement is very attractive since it obviates the necessity of cascading which was required in all of the other forms in order to obtain sufficient intensification to make the device worthwhile.

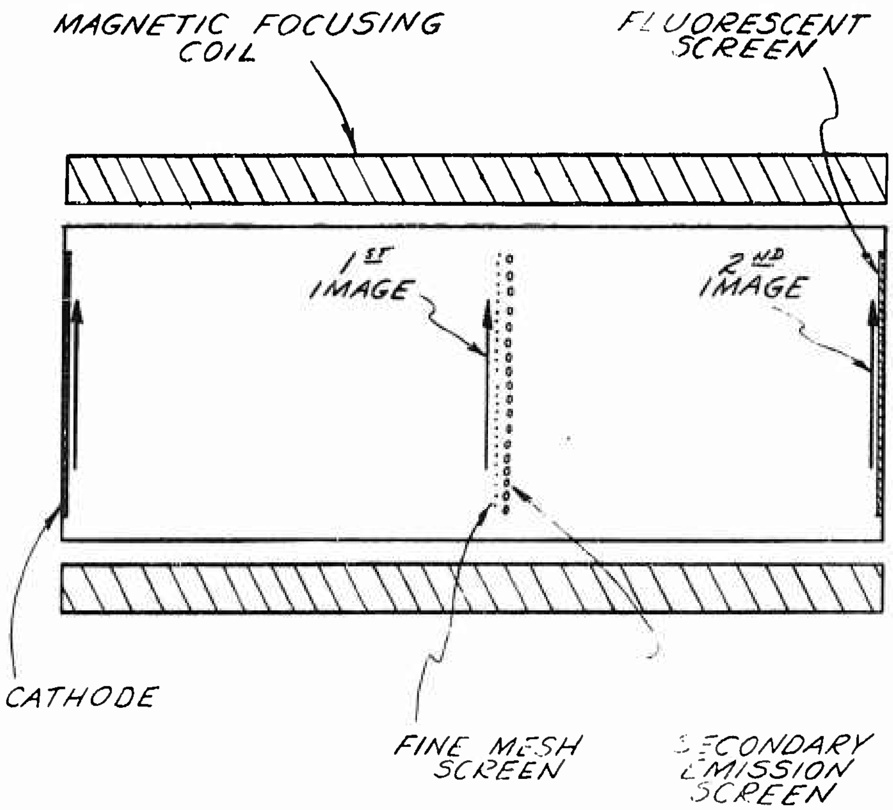

FIG.11 - SCREEN TYPE SECONDARY EMISSION IMAGE INTENSIFIER.

The image amplifier may take any one of a number of forms. Fig. 12 shows schematically one type of image amplifier. A good deal of experimental work has been done on various forms of image amplifiers and some success has been achieved with them. However, this has been primarily in the intensification range where the primary image is already well above the threshold of visibility. So far the image amplifier has not been made to operate at very low light levels.

F. Miscellaneous

The six types of converter tube intensifiers discussed above represent those upon which the greatest amount of theoretical and experimental work has been done. There are, in principle, a great many other ways in which image intensification can be obtained. For example, cellular modifications of almost all of the types of imaging devices are possible. Here, each picture element is handled in a separate electron optical channel which channel may or may not include some provision for enhancing the electron current flowing through it.

In connection with the secondary emission image intensifier, it was mentioned that its greatest weakness was due to the chromatic abberation introduced by the high initial velocities of the secondary electrons. Theoretically it is possible to reduce this chromatic abberation to a large extent by the use of a properly shaped electron mirror. When this is done, however, the overall system becomes much too complicated to be practical.

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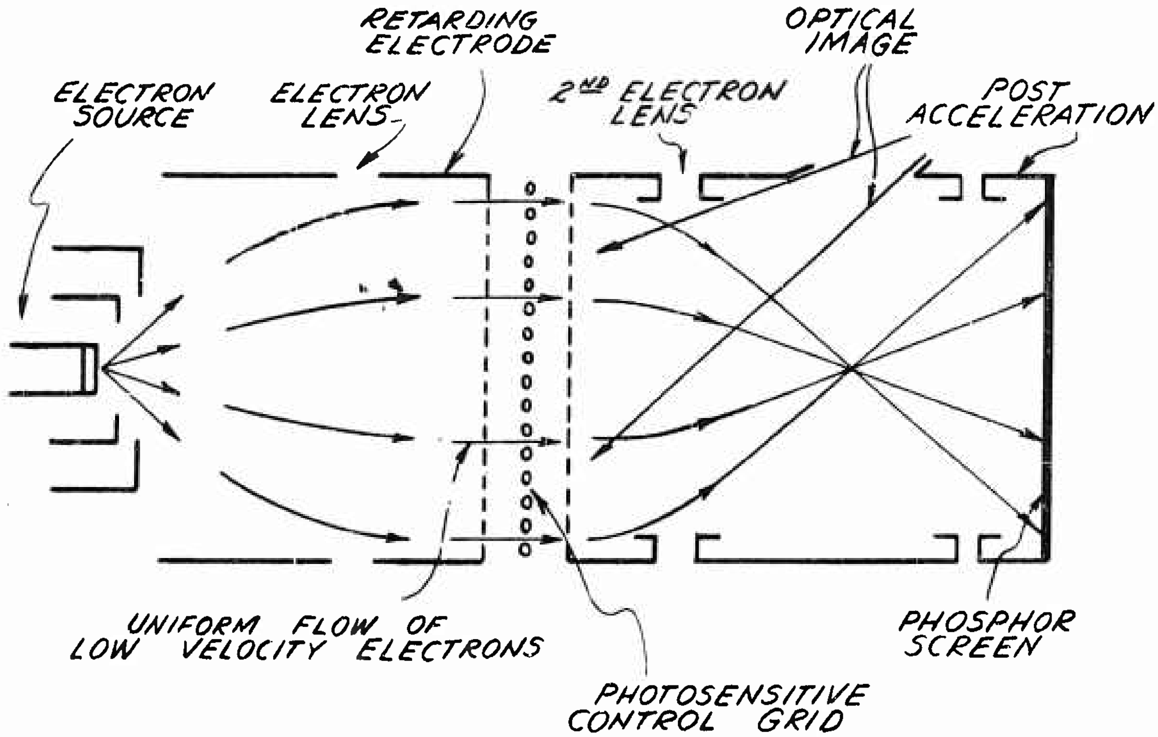

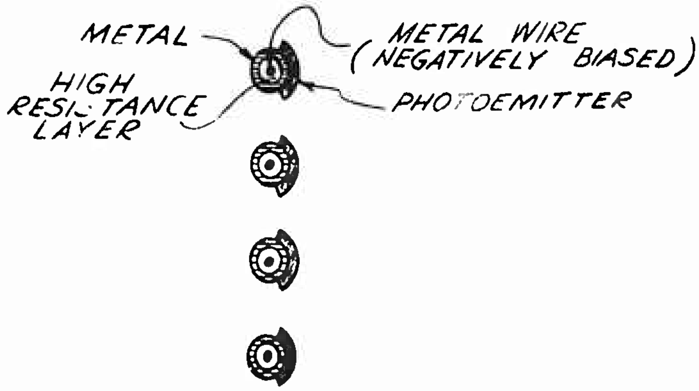

TWO-DIMENSIONAL PHOTOSENSITIVE CONTROL GRID

FIG. 12 - IMAGE AMPLIFIER.

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Finally, some mention might be made of the feedback form of image intensifier. Here, there is optical coupling between the phosphor viewing screen and the primary photocathode. Fig. 13 illustrates the arrangement. The primary image falls on the photocathode and the electrons from it excite the phosphor screen. Light from the phosphor screen returns to the photocathode producing more photoelectrons. This system is a typical feedback system and the relation between the amount of light given out L_2 by an element of the viewing screen to the light incident on the cathode L_1 is as follows:

$$\frac{L_2}{L_1} = \frac{p\beta}{1-p\beta} \qquad (13)$$

where p is the photosensitivity of the photocathode and β is the constant of proportionality between the incident current i on the phosphor screen and the light L emitted by the screen. This type of intensifier is only operative if both p and β are strictly constants. Experimentally it is found that the departure from linearity of light from the fluorescent screen is great enough so as to limit the maximum gain that can be obtained with such a system to about 6. Therefore, this arrangement is not practical for a useful brightness intensifier.

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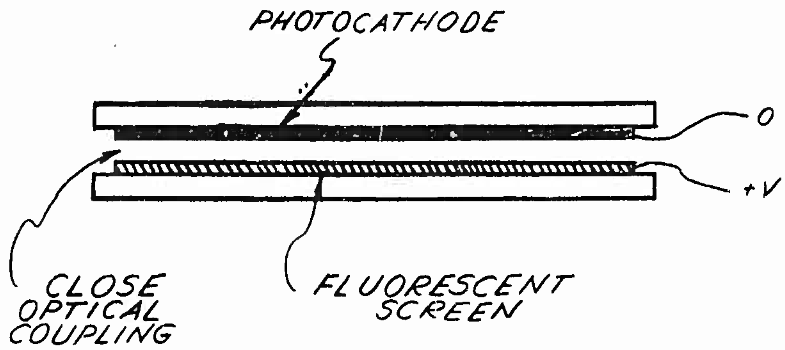

FIG. 13 — FEEDBACK IMAGE INTENSIFIER

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2. Television Type Image Intensifiers

A very interesting form of image intensifiers which may have considerable future practical importance is one where the image formation is taken from the pickup tube in the form of a video signal. This form of intensifier has a number of advantages. Convenience intensification can be obtained simply by the use of sufficient large video amplification. The reproduced image may be located at any point which is convenient to the operator instead of requiring that the operator look at the image through some form of ocular which is closely associated with the pickup tube. Finally, the image may be reproduced at more than one point.

The image orthicon might be though of as the first tube of this class. Here, the primary image is received on a photocathode where it produces an electron image which is focused onto an orthicon target. The orthicon target is scanned by a low velocity electron beam and the video signal is due to the variation in electrons returned from the target and multiplied by a secondary emission multiplier.

The commercial image orthicon falls short of being limited by the photoelectron noise by a factor of almost 100, however. A tube which combines the cascaded phosphor photocathode screen type of intensifier with an orthicon target is shown in Fig. 14. As has already been mentioned, a current gain of about 100 can be obtained from two stages of intensification in a cascaded tube. This is sufficient to bring the

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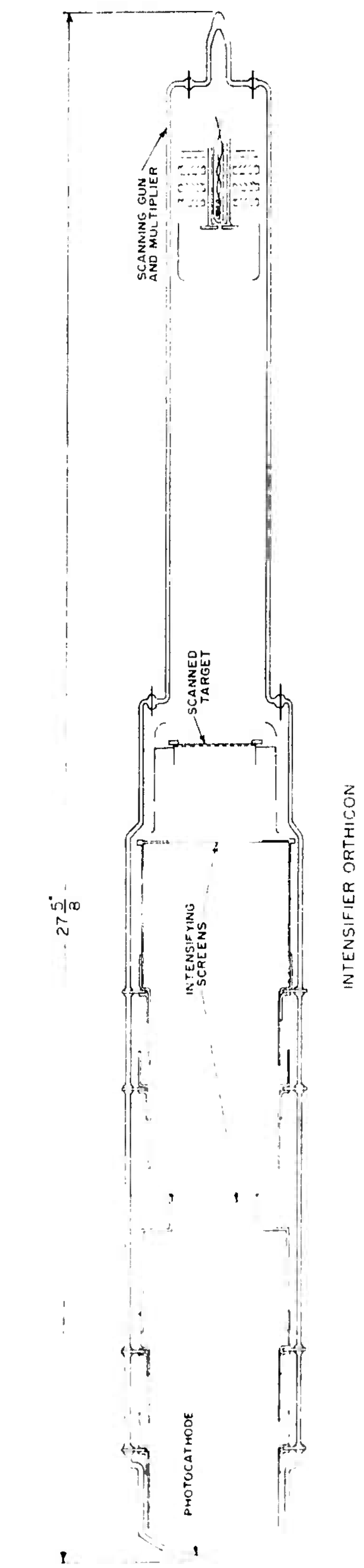

Fig. 14 - Intensifier Orthicon

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sensitivity of the orthicon up to the limit imposed by the photoelectric effect at the primary cathode. This is all of the useful intensification which can be achieved. Any additional convenience intensification which may be desired can be obtained simply by using a high gain video amplifier between the viewing tube and the pickup device.

Experimental work is at present in progress on this type of tube, particularly in connection with its application for intensifying x-ray images. Fig. 15 is a photograph of a tube constructed for this purpose. The experimental work has not been carried far enough to fully establish its working characteristics. However, it seems to hold out a promise of having a much wider field of usefulness than that represented by x-ray image intensification only.

3. Photoconductive Image Intensifiers

The importance of having a high primary quantum efficiency in the photosensitive surface which receives the direct image of the scene being viewed by the intensifier was established in the introductory section of this report. It was also pointed out that photoconductors may have photoconductive responses which are very close to unity quantum efficiency over a wide spectral range. It would seem, therefore, that ultimately the brightness intensifier would be based on this type of interaction between light and electricity. However, in spite of the very great theoretical promise of photoconductors, there is a great deal of research which must be done on these materials

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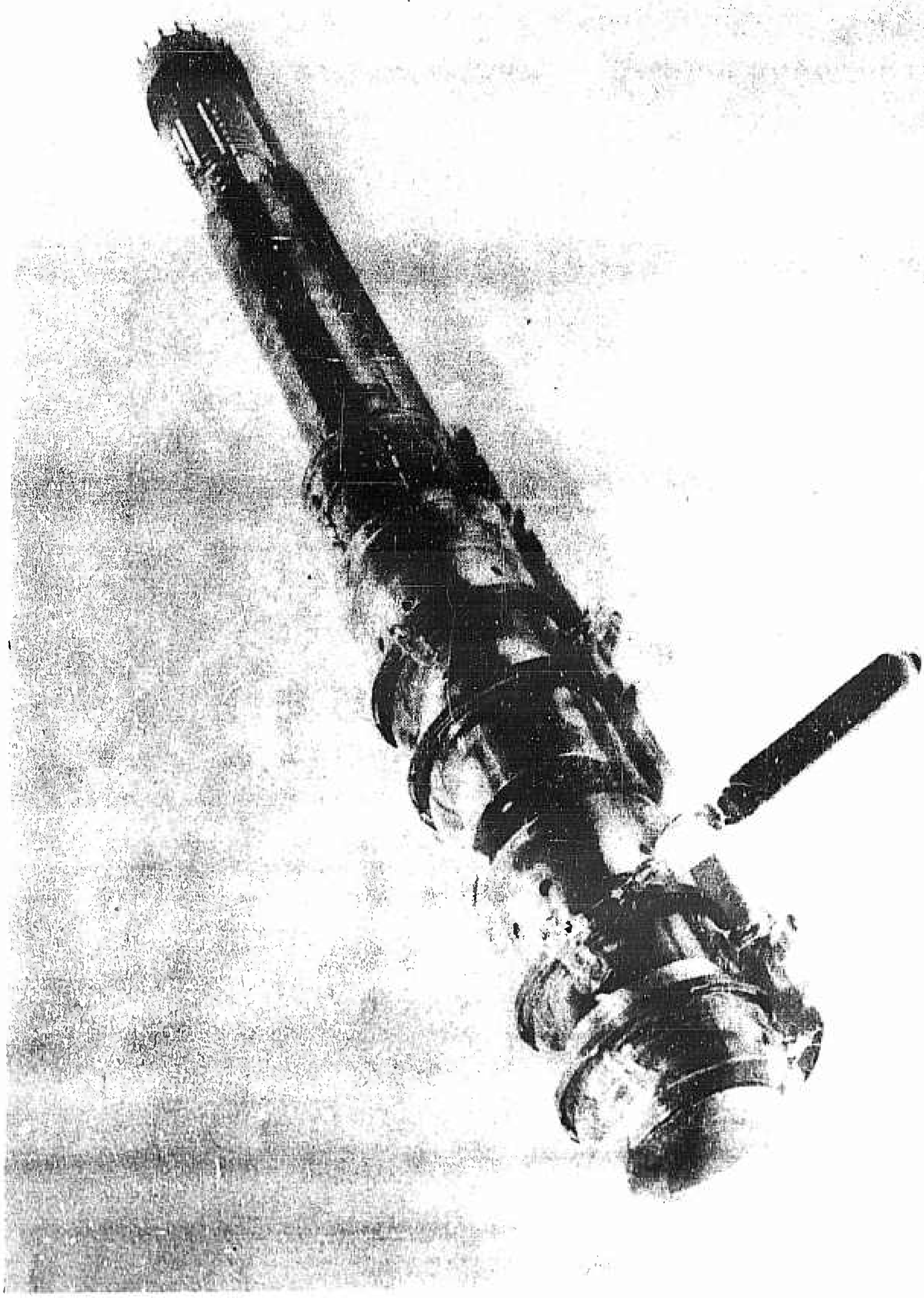

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before they can even begin to compete with intensifiers based on photoemission.

It is true that very small volumes of single crystal photoconductive materials have yielded the high quantum efficiency which might be expected theoretically. However, it has not been possible to obtain large volumes which retain this character of high quantum efficiency. This is particularly true of the thin, high resistance films which are almost essential in any form of image converter device.

There are various ways in which the photoconductive effect may be used in an image brightness intensifier. Four different systems are outlined briefly in the following paragraphs.

A. Vidicon Pickup Tube

Of all of the methods of reproducing an image by the photoconductive effect, the Vidicon pickup tube is the one which has been by far the most thoroughly investigated. Fig. 16 is a diagram showing the arrangement of elements in a special Vidicon.

The photoconductive target which is an essential element of the tube is a thin layer of photoconductive material having the desired spectral response and quantum efficiency and very high specific resitivity. It is supported on one side on a glass plate with a transparent conducting coating on the photoconductor side. The other side of the photoconductor is scanned by a low velocity electron beam. The conducting backing layer is made slightly positive with respect to the cathode

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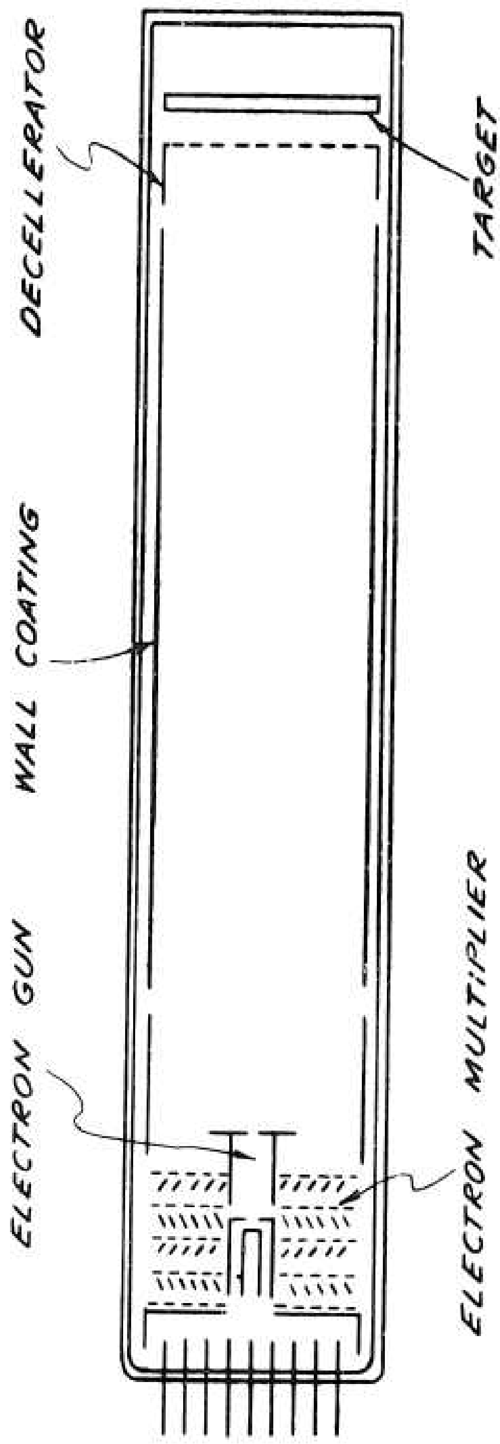

FIG. 16 – BEAM SCANNING PICKUP TUBE.

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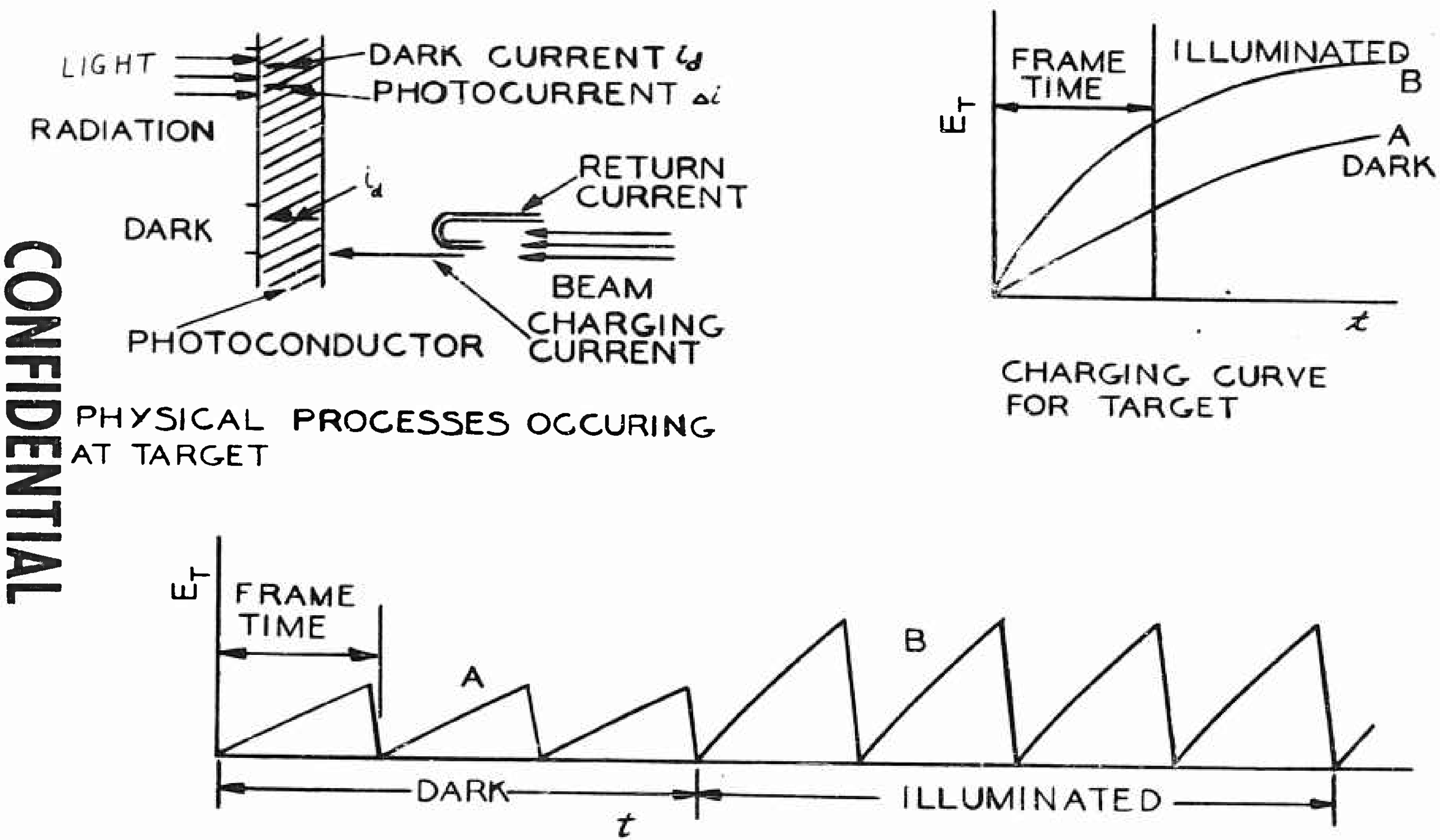

PHYSICAL PROCESSES OCCURING AT TARGET

CHARGING CURVE FOR TARGET

PERIODIC BUILD UP OF CHARGE

FIG. 17. — ELECTRICAL BEHAVIOR OF THE TARGET.

of the gun producing the electron beam. In darkness, as the scanning beam moves over the surface of the target, it brings each element of the surface down to essentially cathode potential. After the beam moves away from a particular point of the target, this point starts going slowly positive due to the current which flows from the back layer to the face of the target. Before the element reaches an appreciable fraction of the voltage difference between the cathode and the backing layer, the scanning beam returns to it again and drives it back to cathode potential. This is shown as curve A of Fig. 17. If an area of the target is illuminated, it goes positive at a much faster rate after the scanning beam passes over it due to its higher conductivity. This is shown as curve B of Fig. 17. As a result, a larger charge accumulates during the time the beam is away from an illuminated element than does when the element is not illuminated. The charge taken from the beam, in order to bring the element back to cathode potential, is consequently greater. Therefore, as the beam moves over the target, when it passes an illuminated area, the electrons returned from the target (i.e., not absorbed in reducing the potential of the target) are lower than for a similar area which is not illuminated. The returning electrons are multiplied in a secondary emission multiplier and the output is the video signal.

With present known target materials, an effective photosensitivity of about 50 to 100 μa/lumen can be obtained with this type of Vidicon target. However, it can be shown analytically, if the target were made of an ideal photoconductor,

that there would be almost a millionfold increase in sensitivity. Eventually, it should be possible to approach this ideal sensitivity, but for the present, the Vidicon type of tube is lower in basic sensitivity than the image Orthicon.

B. The Mirror Image Tube

A second way of applying photoconductivity in an image intensifier is illustrated in Fig. 18. The sensitive area is again a high resistant photoconductive target. Instead of being bombarded by a scanning beam, it is flooded with a uniform spray of electrons which have as nearly as possible the same velocity and direction of approach over the entire surface of the photoconductor. These electrons arrive with a velocity so low that the secondary emission ratio is less than unity. In darkness the surface potential of the target approaches that of the electron source and most of the electrons are reflected from it. These reflected electrons pass through an electrostatic electron lens and are imaged on a fluorescent screen. If an area of the target is illuminated, the higher conductivity of this area causes a greater percentage of the bombarding electrons to be absorbed and consequently a reduction in the electrons reflected back from this area of the target. Thus, a negative image is formed on the fluorescent screen.

Some experimental work has been done along these lines, but so far the sensitivity achieved is far below that of the Vidicon type pickup tube. This is largely because of the difficulty of obtaining suitable uniformity of direction and velocity of the spray of electrons. It also has the disadvantage of producing a negative rather than a positive image.

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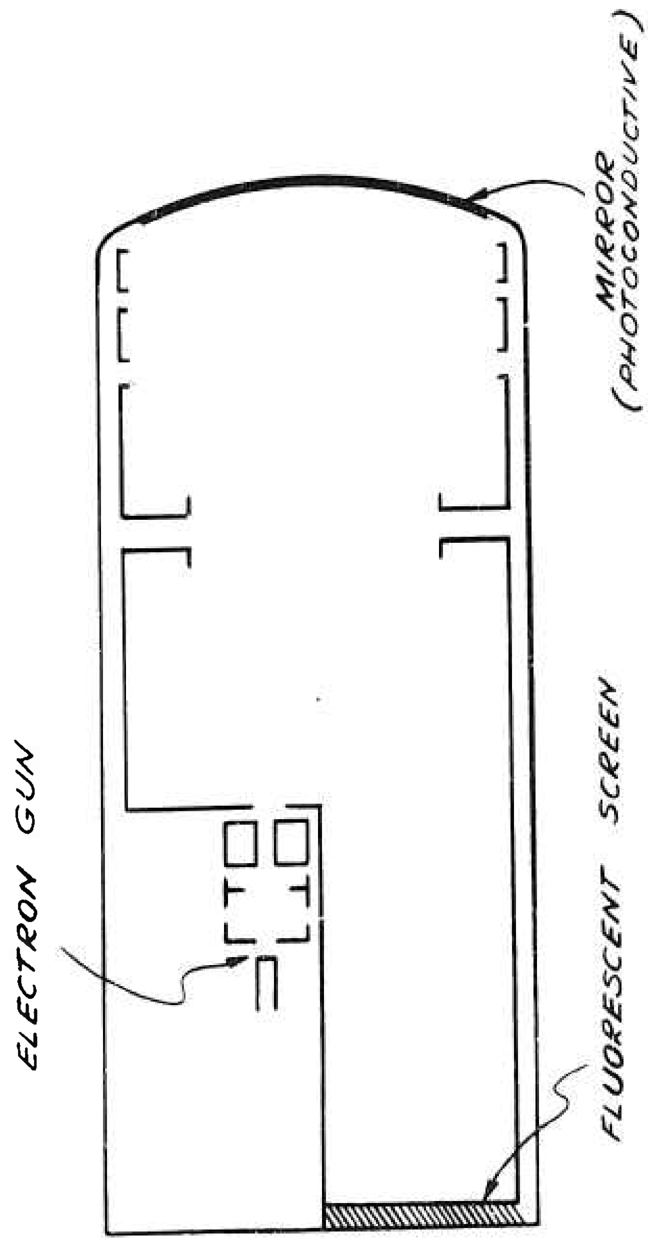

FIG. 18 – MIRROR IMAGE TUBE.

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C. Velocity Selector Image Tube

Closely related to the mirror image tube is the velocity selector converter which also employs a photoconductive sensitive area. Diagram A of Fig. 19 shows an arrangement of this tube. The photoconductive target is shown in detail in diagram B. Like the target in the Vidicon, the back of the photoconductor makes contact with a transparent conducting film. The front is coated with a large number of electron emitting islands. This emission can be due to low temperature thermionic emission or to ultraviolet photoemission excited in such a way that the illumination does not effect the photoconductor. For example, between the islands and the photoconductor a high resistant color filter may serve to prevent light which produces the photoelectrons from reaching the photoconductor. The electrons which are emitted from the target are accelerated away from the target by an electrostatic lens system which is arranged in such a way that an image of low velocity electrons are formed on the stopping screen B. In darkness the resistance of the photoconductive film is vey high and the IR drop due to the photoemission current flowing through the photoconductor causes the emitting islands to be quite positive with respect to the backing plate. This in turn causes the electrons which approach the two-dimensional control grid D to have so low a velocity that they do not get through this grid. If an area of the photoconductor is illuminated, its resistance decreases and the emitting islands are less positive. Consequently, electrons from this area reach the control grid with a higher velocity (since they come from a more negative cathode area)

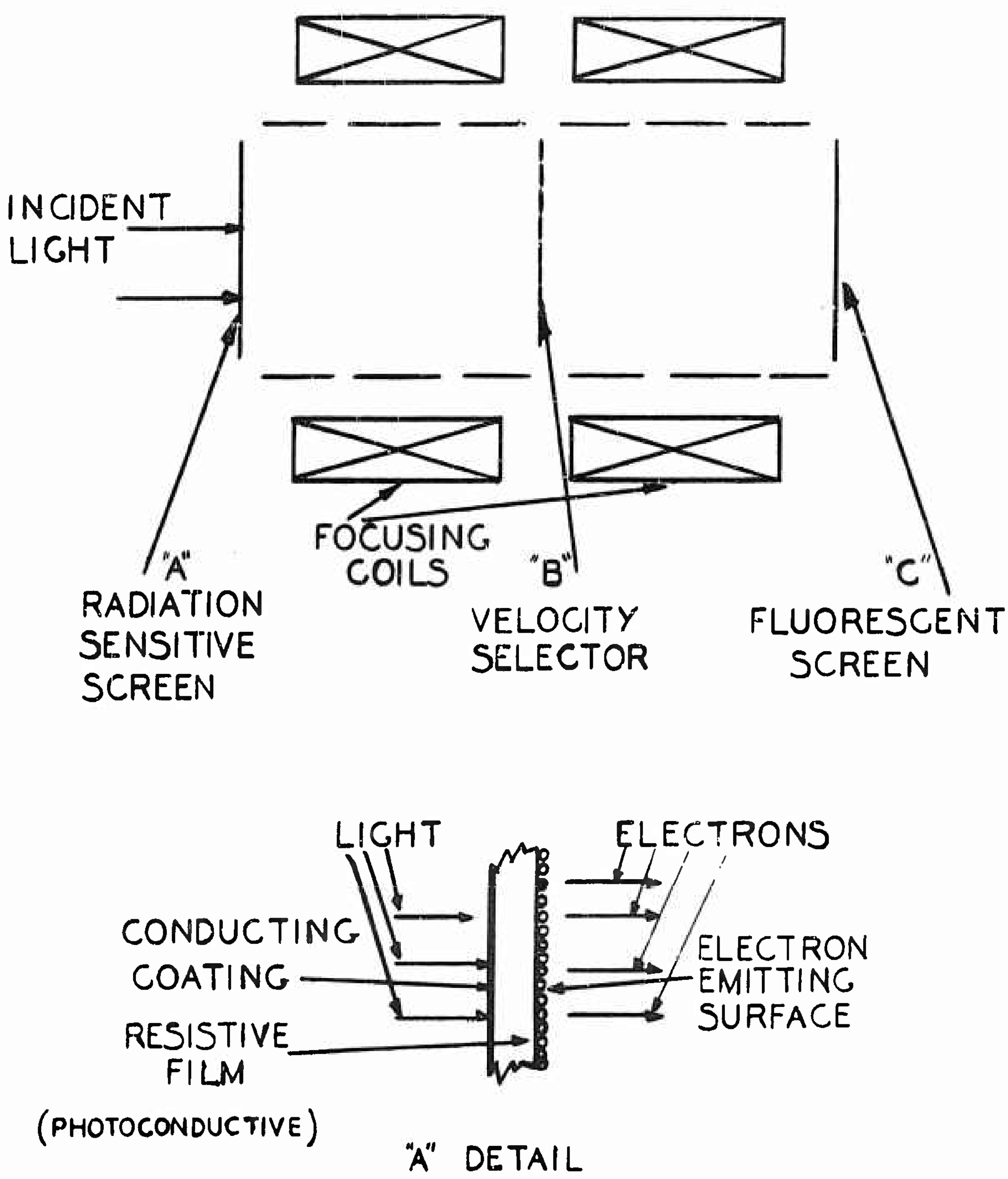

FIG. 19 – VELOCITY SELECTOR IMAGE TUBE.

and they will pass through the control grid. Electrons getting through the control grid are again accelerated and imaged on a fluorescent screen where they produce a visible reproduction.

This type of velocity selector image tube produces a positive image of the scene focused on the photoconductive film. A small amount of experimental work has been done on this form of intensifier. It has been demonstrated that the velocity selection performed at the control grid B does not interfere with the imaging process and that a sharp undistorted image may be obtained with such a control grid. The sensitive photoconductive emitting screen presents a severe technical problem which has not yet been solved. While this type of imaging system has many attractive properties, it is rather doubtful that it will ever receive much developmental attention in view of the very great promise of the Vidicon type pickup tube.

D. The Electroluminescent Photoconductive Intensifier

A final form of image intensifier which may eventually make all of those described above obsolete is one which, instead of using an electron stream bombarding a fluorescent screen to produce the luminous image, employs electroluminescence. Electroluminescence is the property of certain phosphor materials to glow when a field is applied across them causing a current to flow. Fig. 20 shows a possible arrangement of a photoconductive image intensifier based on an electroluminescent viewing screen. A is a transparent conducting film which the layer B is the photoconductor. C is a conducting region which optically separates film B from the electroluminescent screen C.

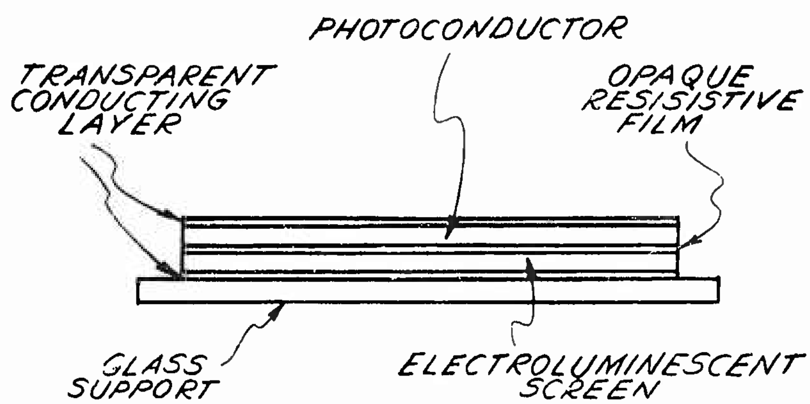

FIG. 20 – ELECTROLUMINESCENT INTENSIFIER.

This layer of material has very low conductivity in the direction of its surface but will conduct electricity at right angles. Insulated metal elements, for example, would have this property. On the other side of the electroluminescent screen there is again a transparent conducting coating E. A potential is applied between A and E. In darkness the photoconductive layer has very high resistance and consequently no current flows through the electroluminescent screen. When an area of the photoconductor is illuminated, a current can flow through this region and on through the electroluminescent screen as well. This causes the latter to become luminous. In this way, a luminous replica of a light image projected on side B is formed on the electroluminescent screen D. A good deal of work is being done at present on various phases of electroluminescent surfaces and also upon the combination of photoconductors with the electroluminescent phenomenon. However, this type of device has not yet been developed to the point where any test can be made as to its feasibility when applied to the problem of the brightness intensifier. It is a technique which holds forth great promise for the direct view intensifier device. It might be pointed out that with this system no large vacuum envelope is involved nor does it require electron optics. The whole structure is simple and direct and therefore should be rugged, reliable and longlived. It probably represents an extremely important future development in this field.

PART III

A BRIGHTNESS INTENSIFIER RECEIVER WITH CASCADED IMAGE TUBE CONVERTER

As was mentioned in an earlier section, most of the experimental work on brightness intensifiers has been done with receivers based on cascaded image converter tubes. Three complete receivers of this type have been constructed for the Bureau of Ships, Navy Department. These receivers employed Schmidt reflector objectives, two-stage image intensifier tubes and binocular eyepieces for viewing the final image. Both laboratory and field tests were made with these units and the data obtained is probably sufficient to permit a fairly well founded appraisal of this class of device.

A converter tube of the type employed in these units is shown photographed in Fig. 21. Fig. 22 is a diagram of the construction of the tube. The cathode is about three inches in diameter and sensitized with a cesium-antimonide film. The electrostatic lens which images the photoelectrons onto the first intensifier screen is designed to minimize cold discharge, which is the main source of non-fundamental background. The intensifier screen is formed on a film of glass less than 1 mil thick. This film is formed with a radius of curvature of three inches and mounted with the convex side toward the first cathode. Silver-activated zinc-sulfide is settled on the convex side of the screen and is protected by a thin layer of aluminum on collodion in the usual way. The cesium-antimonide photocathode

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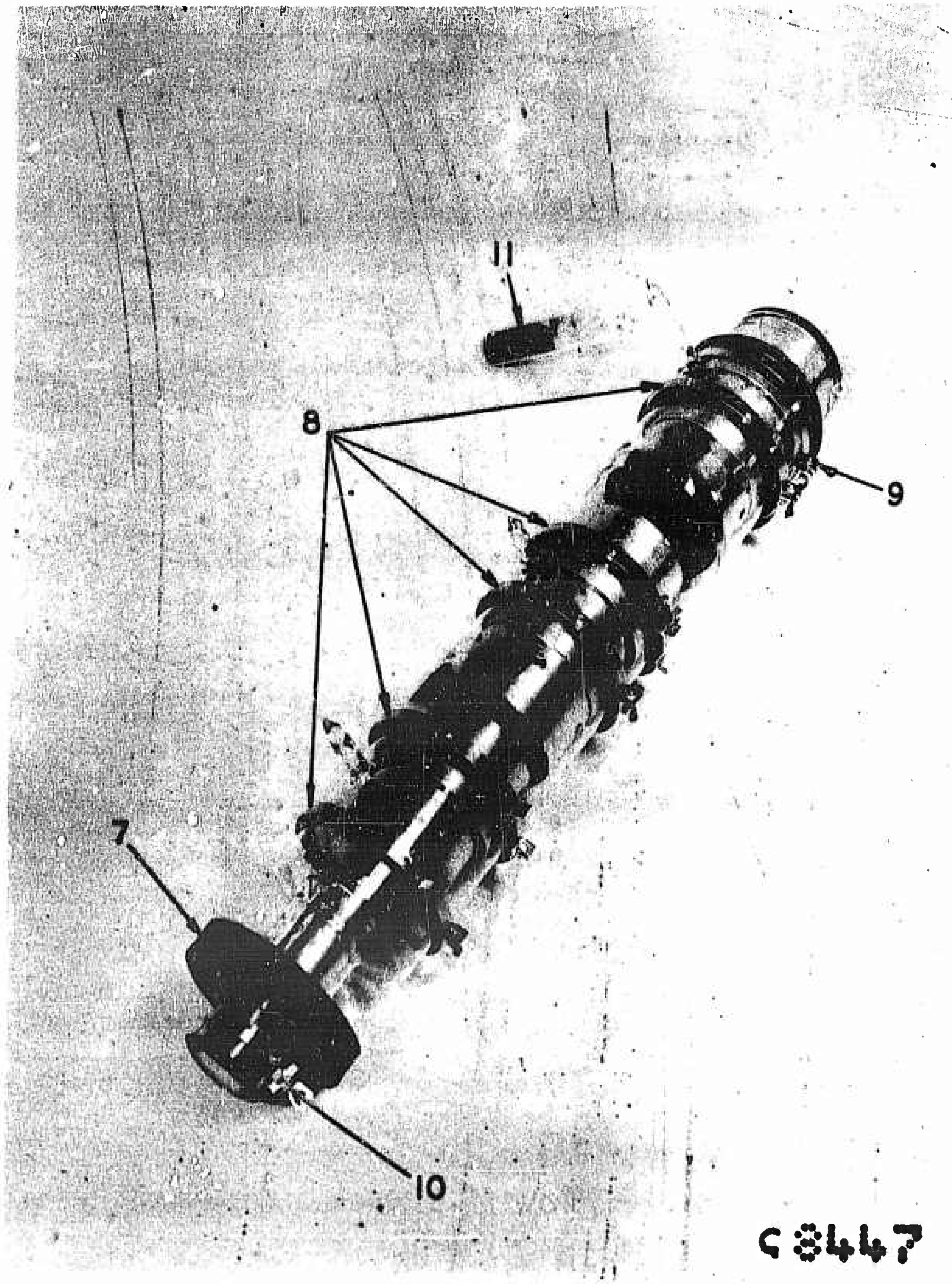

Fig. 21 - Photograph of Brightness Intensifier Tube

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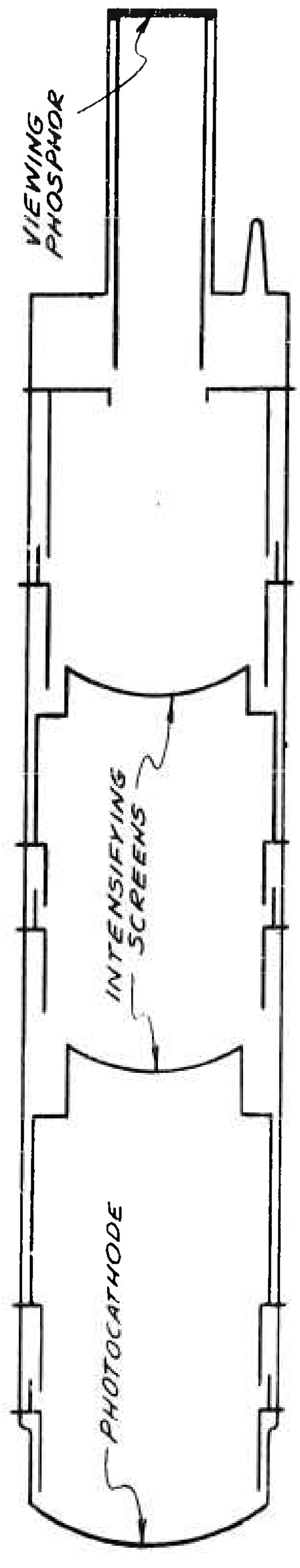

FIG. 22 - DIAGRAM OF BRIGHTNESS INTENSIFIER.

on the concave side is deposited after the tube is assembled and during the activation procedure. The electron optical system which images the electrons from the intensifier screen is very similar to the first lens system. The second intensifier screen is identical with the one just described. The final electron lens system which forms the image on the viewing screen has a magnification of one-half.

In addition to cold discharge, a second source of background spurious signal is due to ions formed in the residual gas in the tube. In order to minimize the amount of gas, these tubes are equipped with a side tube filled with charcoal which, when cooled to liquid air temperature, absorbs any gas which might have been present in the tube.

Each section of the tube operates at an overall voltage of 10 kilovolts. It is not possible to connect the three sections in parallel since the thin glass films of the intensifier screens will not support the 10 KV potential difference through them. Consequently, a total voltage of 30 KV is required for these units. Fig. 23 shows the circuit diagram of the battery-operated power supply which was designed for these instruments.

The tube is supported on insulating cradles mounted in a cylindrical housing which must be large enough to hold the voltage divider without corona and other electrical discharge. This last is very important since even the faintest light generated along the sides of the tube will introduce a background which seriously affects the threshold of the device. The Schmidt system is attached to the end of the cylinder.

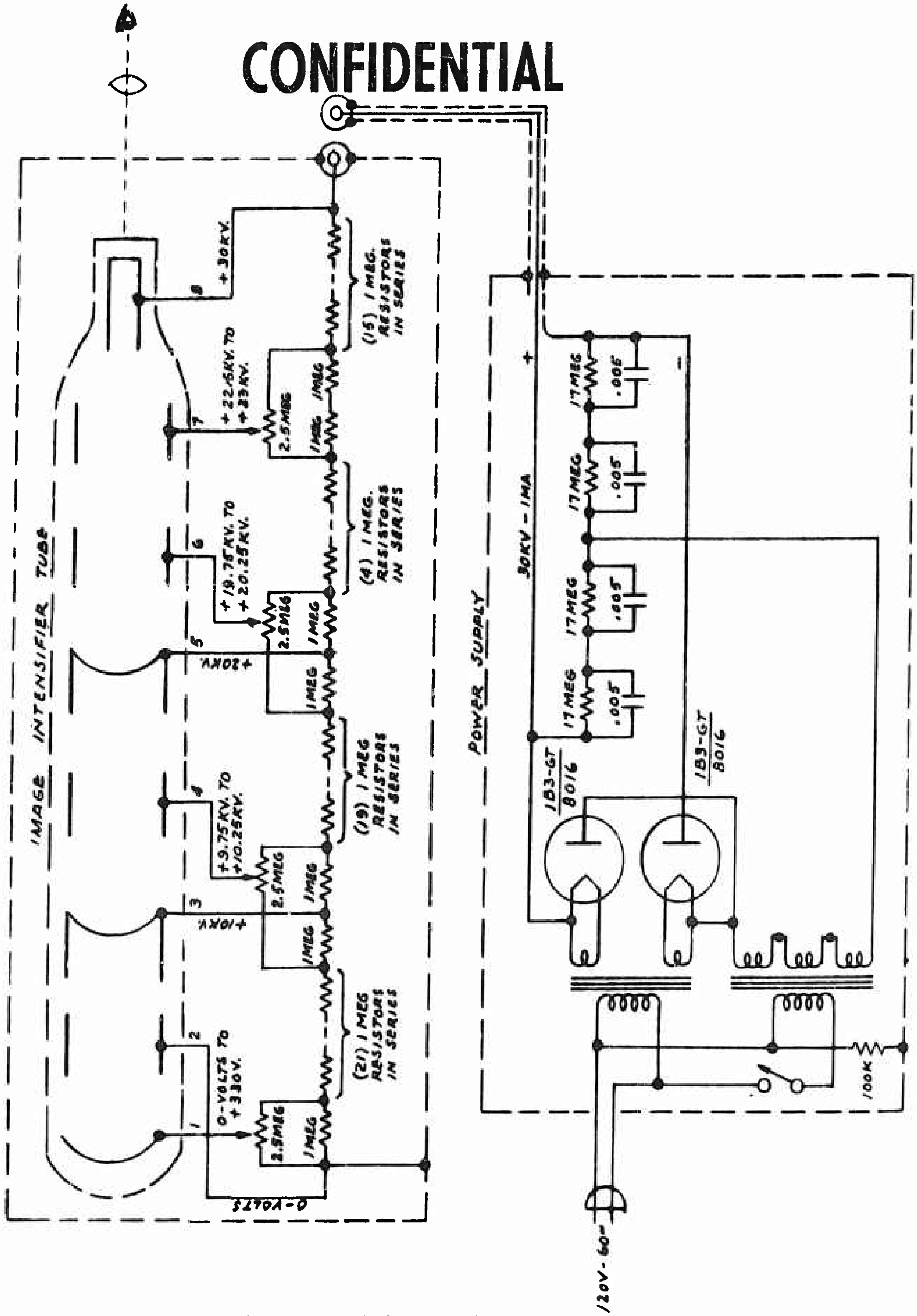

Fig. 23 - Electrical Supply for Intensifier Telescope

The Schmidt system is folded so that the image is projected back through a hole in the center of the spherical mirror. Focusing is achieved by moving the plane mirror which folds the image back. The focal length of the Schmidt is about seven inches and its geometric aperture about F/0.7. Its effective light gathering power corresponds to an optical system of F/0.9 to F/1.0. The spherical reflector is a front surfaced glass mirror while the corrector plate is formed of plastic. A six-power binocular eyepiece is used to observe the final image. The overall magnification of the entire telescope is slightly more than two times. The appearance of the complete unit is shown in Fig. 24.

Very thorough performance tests were carried out on receivers of the type described above. In complete darkness the background of the viewing screen was very low. As nearly as it could be measured, the brightness of the background was not greate than 10^{-5} foot-lamberts. With normal voltage on the intensifier tube, the overall lumen gain of the system was about 500. This intensification is sufficient so that when the cathode was illuminated with a small amount of light photoelectron noise was clearly apparent. The scintillation produced by a single electron from the photocathode was just below visual threshold, although under this operating condition it was not certain that they could not be seen. An intensification sufficient to bring out photoelectron noise is all that is absolutely essential in the brightness intensifier. Further gain may increase the convenience of operation but will not add information to the image.

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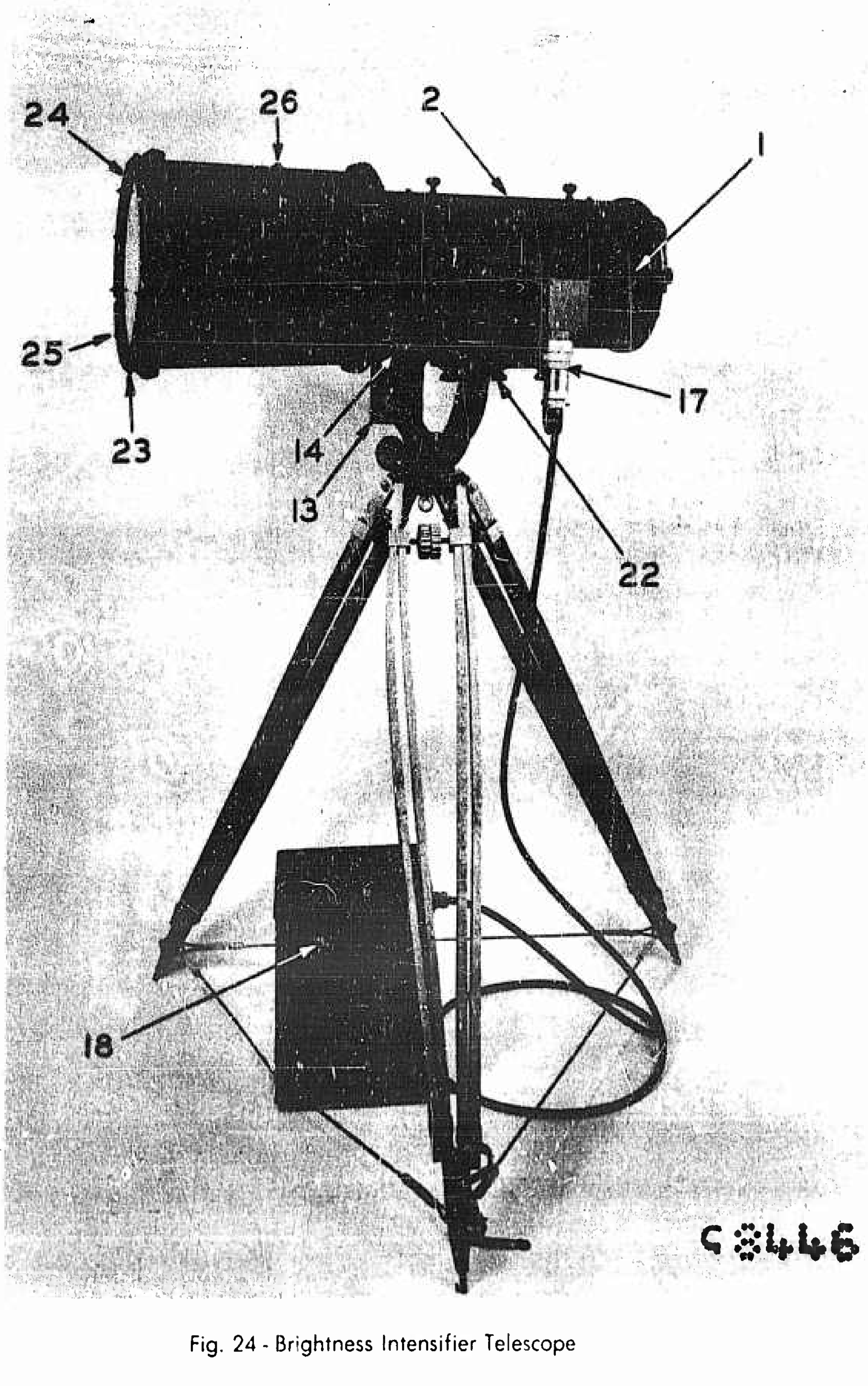

Fig. 24 - Brightness Intensifier Telescope

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In order to make a check on the absolute performance of the system, an objective having a focal length which gave an overall magnification of unity, and an absolute aperture equal to the area of the dark-adapted pupil was substituted for the Schmidt system. The threshold for seeing an object of a given definition was then compared with the threshold for viewing the same object with the unaided eye. It was found that the thresholds were within a factor of 2, slightly more light being required with the intensifier system was used. Since the quantum efficiencies of the photocathodes which were achieved in these tubes were comparable to that of the eye, this result can be interpreted to mean that the optical losses in the objective system are slightly higher than those in the eye. This performance was considered very good. Before the experiment was performed, it was assumed that the losses might run as high as four or five times those of the eye.

Laboratory tests using an objective four inches in diameter were made to determine the relative ability to see a series of test patterns with the telescope and with the unaided eye. The threshold of seeing was improved by a factor of from 64 to 100 when the telescope was used. If the system were ideal, the improvement should have been 250. The loss factor was not considered unreasonable in view of the fact that the objective used was quite complex and employed a large number of elements.

In addition to laboratory tests, field tests were made with these receivers. These tests were qualitative rather than quantitative but did give a good indication of what might

be expected from the device in the field. It was found possible to distinguish objects which could not be seen with the unaided eye quite readily when the telescope was used. When compared with night glasses with 50 mm objectives and seven-power magnification, it was found that the intensifier receiver gave slightly better performance. This did not take into account the fact that the telescope gives a very much wider angle of vision and consequently much more total information in the image than does a high-power night glass.

An interesting observation was made when the instrument was used for outdoor night-time work. At the very low light levels the operator got a definite impression that the contrast was quite low in comparison with the contrast observed with the unaided eye. This is apparently due to the non-linear behavior of the eye close to visual threshold. There is a tendency here to greatly exaggerate the differences in contrast. It has been long recognized that objects when seen by moonlight appear to have harsh spectacular contrast. Manv ameteur photographers have been keenly disappointed when, after seeing a moonlight scene with its striking contrast, they have attempted to photograph the scene with a long exposure. Upon processing such pictures, they are found to have only the normal daylight contrast. This effect exists very strongly in the brightness intensifier at low light levels and gives the uninformed observer the feeling of not being able to see as much as he should see. Actually, the harsh contrasts seen near threshold do not contribute to the information seen, and consequently

the lower apparent contrasts of the intensifier image do not really represent any loss in ability to either discriminate detail or contrast steps.

The overall performance of these instruments was almost exactly as one might predict. The gain in seeing is the result of having a large aperture objective. Such an objective cannot be used in a direct optical instrument without very greatly decreasing the angle of vision. In other words, when such an objective is used in an optical telescope the total information in the image seen is small, whereas with a brightness intensifier employing the same diameter objective a wide angle of vision is retained and the picture contains a large amount of information. However, for most practical field applications, the large size and weight and the complexity of the brightness intensifier receiver more than offsets the advantage gained by having a wide angle of view. When an observer is using night glasses which are small and easily moved, he can readily make up for lack of field of view by simply moving his glasses. Except for very special circumstances, therefore, it is not possible to justify the field use of a brightness intensifier image tube.

PART IV

CONCLUSION

Studies of the performance of the human eye indicate that its threshold is essentially determined by the fundamental noise in a system whose quantum efficiency is ten percent. A brightness intensifier which is to give the observer more information than he can obtain with the unaided eye must, therefore, either employ a sensitive surface having greater than 10% quantum efficiency or an objective with a larger absolute aperture.

Extensive research is being carried on in many laboratories to obtain materials having photoelectric response with greater quantum efficiency. Photoemitters may have as much as 25% quantum efficiency in the blue parts of the spectrum while certain small crystal elements exhibit photoconductivity with a quantum efficiency of nearly unity. There is reason to believe, therefore, that eventually it will be possible to make an electro-optical converter system which has close to unity quantum efficiency; in other words, a factor of 10 over the unaided eye. This, however, is not realizable at present.

The brightness intensifiers which have been investigated depend for their action upon a large objective. They are, therefore, large, cumbersome and complicated. Where the device is in the form of a direct view image tube, their general field use cannot be justified. There may be certain special situations where they are required. One of these might be where the

observer is required to work in an environment which does not permit him to become dark-adapted and yet where he must observe an outside scene where the light level is very low. Another situation is where the observer is stationed in such a position that he must observe a large angle of view yet does not have the mobility necessary to cover this same angle of view with ordinary night glasses. The application to x-ray fluoroscopy is another non-military possibility.

If the relatively simple electroluminescent converter device described in section III (D) can be developed, it is potentially sufficiently simple and lightweight that the situation should be reviewed again.

Where the brightness intensifier produces a video signal instead of a direct view image, there is a much greater possibility of practical application. One of these is for the equipment to be mounted on either a manned or unmanned aircraft. The signal can then be viewed by the operator (if any) of the airplane and also transmitted to a ground station where it can be analyzed in detail.

Other situations are where the viewer is mounted at outposts, on towers, or at other locations where it can maintain surveillance and the signal brought into an observation station by wire or radio. In other words, such a system has all the advantages of television plus the added advantage of being able to see under conditions of illumination which do not permit satisfactory vision with the unaided eye.

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